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FAILURE RATES FOR FIBER OPTIC ASSEMBLIES

IIT Research Institute

Steven Flint

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This report presents updated reliability prediction models for those components used in fiber optic assemblies. Device types considered include light emitting diodes (LEDs), light emitting diode (LED) displays, laser diodes, phototransistors, photodiodes, optically coupled isolators, fiber optic cables and fiber optic connectors.

The reliability prediction models are presented in a form compatible with the existing models of MIL-HDBK-217C.

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Fiber optic connector
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PREFACE

This final report was prepared by IIT Research Institute, Chicago, Illinois, for the Rome Air Development Center, Griffiss AFB, New York, under Contract F30602-79-C-0161. The RADC technical monitor for this program was Mr. Lester Gubbins (RBET). This report covers the work performed from June 1979 to August 1980.

The principal investigator for this project was Mr. S.J. Flint with valuable assistance provided by Dr. T. Hsu, Mrs. C.A. Proctor, Mr. H.C. Rickers, Mr. P.A. Mihalkanin, Dr. C.E. Ehrenfried and Mr. D.W. Fulton. Data collection efforts for this program were coordinated by Mr. I.L. Krulac and Mr. J.P. Carey.

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EVALUATION

This contractual effort is part of the broad RADC Reliability Program intended to provide reliability prediction, control and demonstration procedures for military electronic systems and equipment. The prediction procedures are contained in MIL-HDBK-217C for which RADC is the preparing activity. The failure rate models developed in this study are an improvement over the existing models and will be included in the next issue of MIL-HDBK-217. This effort is responsive to TPO IV F2, Equipment/System Reliability & Maintainability.

Lester J. Gubbins
LESTER J. GUBBINS
Project Engineer

SECTION 1
PURPOSE

The purpose of this study was to develop a failure rate prediction methodology which could be employed in the reliability assessment of fiber optic and optoelectronic components and assemblies. Device types considered include fiber optic cables, fiber optic cable connectors, light emitting diodes (LEDs), light emitting diode (LED) displays, laser diodes, phototransistors, p-i-n photodiodes, avalanche photodiodes (APDs) and optoisolators.

The study involved development of failure rate prediction models for those component types not currently addressed in MIL-HDBK-217C, Reliability Prediction of Electronic Equipment, and the modification of any existing prediction models which proved inadequate.

1.1 Background

Recent advances in data processing capabilities brought about by the development of high speed and high density integrated circuits have surpassed existing data transmission capabilities. The use of large bundles of copper wires is becoming less desirable as a means of information transfer. The size, weight, bandwidth limitations and cost of metal conductors have forced scientists and engineers to investigate other means of data handling. Of the several alternatives being developed, fiber optics is one of the most mature and cost-effective solutions for the near future.

Fiber optics offers potential advantages in size, weight, bandwidth, resistance to electromagnetic interference (EMI) and nuclear radiation, and cost when compared with metallic conductors. In a number of applications, however, these advantages are of little or no consequence unless the implementation of fiber optics can also provide reliable data transmission capabilities over the expected life of the system. The recent interest in the use of fiber optic data links in military/defense applications has created a need for a reliability prediction methodology capable of addressing the various components and assemblies used in such a system. Failure rate and mean time between failure (MTBF) prediction capabilities are essential in the development and maintenance of reliable electronic equipment. Predictions performed during the design phase yield early estimates of the anticipated equipment reliability providing a quantitative basis for performing design trade-off analyses, reliability growth monitoring, maintenance action and spares allocation requirements, and life cycle cost studies.

A useful fiber optic component failure rate prediction methodology should afford the optimal consideration of those qualities common to practical reliability assessment techniques including:

- a relatively uncomplicated approach which is easy to use and does not require intimate knowledge of device characteristics beyond readily available information;

- the appropriate discrimination against device design and usage attributes which contribute to known failure mechanisms;
- a dynamic, flexible expression, which, through simple modification, allows for the evaluation of newly emerging technologies or devices;
- reasonable accuracy over the total range of all parameters considered in the technique.

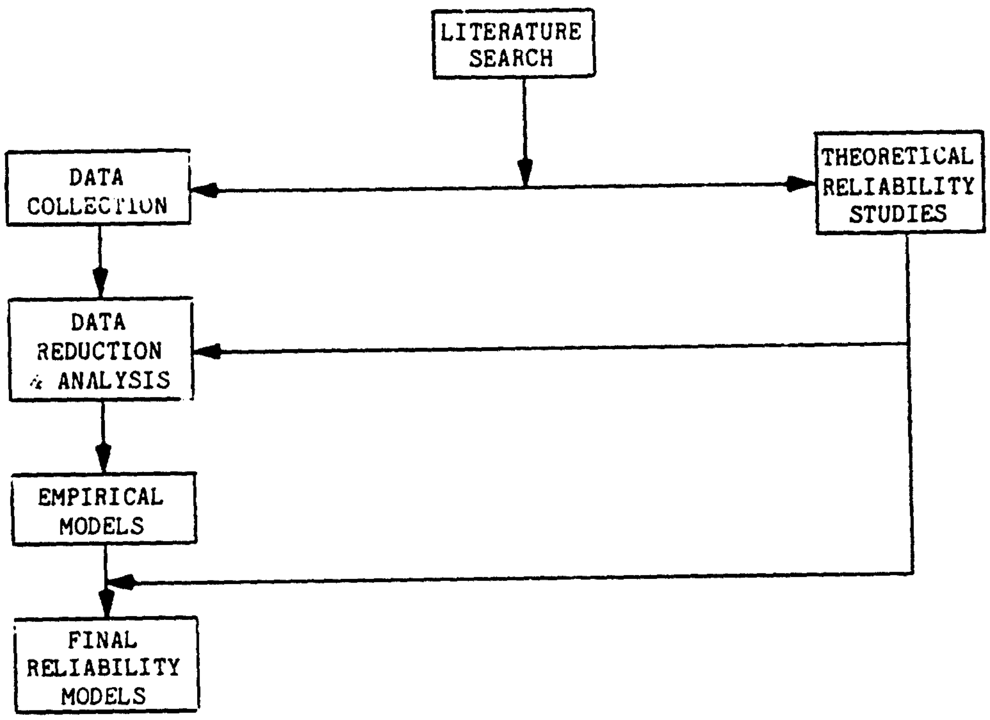
The report describes the approach, results, and conclusions of the study and includes the proposed optoelectronic component reliability prediction models to update Section 2.2.10 of MIL-HDBK-217C. Also, point estimate failure rates for fiber optic cables and fiber optic connectors are proposed as an addition to the "Miscellaneous Parts" Section 2.14 of MIL-HDBK-217C.

SECTION 2

DEVELOPMENT OF RELIABILITY PREDICTION MODELS

A flow chart presenting the approach used in this study is presented in Figure 2.1. This figure details the emphasis placed on the development of models having a sound theoretical basis. Early in the program, a heavy emphasis was directed towards the identification of the actual failure mechanisms observed in each device. Once identified, the mechanisms were further studied to determine accelerating stresses and conditions. Attention was also paid to those design guidelines which could result in more reliable operation. For those device types where field data was limited, these considerations could be combined with whatever data was available to develop a useful model. In those instances where no field data could be identified, the theoretical discussions will provide the engineer with qualitative indications of the reliability of the component. When field information does eventually become available, the theory will augment the data to provide maximum utility to the reliability analyst.

Section 2 presents a summary by task of the reliability prediction model development activities. The proposed models are presented in Section 3.



FLOW CHART OF MODEL DEVELOPMENT

FIGURE 2.1

2.1 Literature Review

A comprehensive literature review was performed to identify all published information which is relevant to the reliability of fiber optic components. Literature sources searched (in addition to the RAC automated library information retrieval system) include the National Technical Information Service (NTIS), the Defense Technical Information System (DTIS) and the Government Industry Data Exchange Program (GIDEP).

The emphasis in the literature review was directed toward the identification of references dealing specifically with fiber optic and/or optoelectronic reliability characteristics and prediction. Reliability prediction references were examined to determine the deficiencies of current prediction methods (where they existed) and to evaluate the merit of proposed prediction model revisions. Other reports were extremely useful in providing supplemental information, particularly in the areas of component construction, testing, and failure modes and mechanisms. An extensive bibliography was compiled as a result of this literature search, and it is included at the end of this report.

2.2 Theoretical Discussions

In order to fully utilize the data collected and provide the reliability models with a sound theoretical foundation, an effort was undertaken early in the program to investigate the fundamental physical and electrical characteristics of each device type in order to identify those parameters having a significant impact on component reliability. This section will summarize the results of that effort. Each generic device type will be considered separately.

2.2.1 Light Emitting Diodes (LEDs)

A light emitting diode is similar to any other semiconductor diode in that it consists of a p-n junction which conducts current only when biased in the "forward" direction. Unlike ordinary diodes, however, the LED emits light when forward biased.

Light is produced when electrons and holes recombine, emitting photons. By careful control of materials and processes, the bandgap of the semiconductor (and hence the wavelength of the emitted light) may be controlled.

At present, LEDs are manufactured from GaP, GaAs, or GaAsP. The use of several other semiconductor materials are in various stages of development, but the gallium-based semiconductors presently dominate the market.

As would be expected, the LED is vulnerable to all common diode failure modes and mechanisms, as well as several which are unique to light emitting types. Since semiconductor diode failure modes and mechanisms are well understood and well documented, this report will address only those reliability problems unique to LEDs.

The principle failure mode of light emitting diodes is that of degraded light output. The effects and occurrences of such degradation are

much better documented in the literature than are its causes. Recent studies suggest two separate mechanisms, each of which results in a gradual fall-off of light output from an LED. These two mechanisms are dark line defect (DLD) formation and uniform degradation.

As the name implies, dark line defects appear as small erratic lines on an LED chip from which no light emission is observed. DLDs result from the development of vacancies or interstitial dislocation loops (crystal lattice defects). Fortunately dark line defects may be prevented by carefully controlling the growth and processing of the semiconductor crystals. The rate of DLD degradation depends on the level of actual mechanical stress applied to the chip as a result of environmental conditions such as mechanical shock, vibration, and thermal expansion/contraction. LEDs exhibiting dark line defects typically end as infant mortality failures.

A second type of light output degradation occurring in LEDs is known as uniform degradation. Uniform degradation proceeds at a slower rate than that due to dark line defects and as a result is usually observed only in LEDs free of dark line defects. This degradation is a result of increased concentrations of non-radiative recombination centers and point defects with energy levels deep in the forbidden gap. This mechanism exhibits a strong temperature dependence and is independent of optical power output.

High temperature testing and life test data have shown the temperature dependence of LED failure rate to be approximately exponential with

$$\lambda = A \exp\left[-\frac{E_{ea}}{kT}\right] \text{ where;}$$

λ = failure rate

A = normalization constant

k = Boltzmann's constant = 8.63×10^{-5} eV/°K

T = device operating junction temperature (Kelvin)

E_{ea} = equivalent activation energy (eV)

The equivalent activation energy, E_{ea}, is intended to show that the failure rate of a particular device type exhibits essentially the same temperature dependence as a device failing due to only one failure mechanism having an activation energy $E_a = E_{ea}$. Since an activation energy E_a may only be associated with a specific mechanism, when speaking of the temperature dependence of failure rate of a device failing due to the cumulative effects of several mechanisms, it is reasonable to express the gross temperature dependence of failure rate for that device in terms of an equivalent activation energy E_{ea}. It should be understood that while E_a is a constant, valid at any temperature, E_{ea} will be approximately constant only for a limited temperature range. Still for many circumstances, the concept of equivalent activation energy provides a simple, convenient means of expressing the temperature dependence of failure rate for a variety of semiconductor components operating at "typical" temperatures.

Results of various laboratory tests on light emitting diodes have indicated a typical equivalent activation energy E_{ea} of 0.7eV.

2.2.2 LED Displays

LED displays are simply arrays of discrete LEDs packaged in such a manner as to permit representation of numeric or alpha-numeric characters. The LED chips used in such displays are comparable to those used in discrete LEDs. Due to the way displays are used in circuits, however, the failure rate of a display is usually less than the sum of the failure rates of an equal number of discretely packaged LEDs. This apparent inconsistency results from the duty cycling of a display.

The overall duty cycling of displays results from three separate sources. First is the common duty cycling of a display wherein power is supplied to the display in pulses in order to conserve power, lower the operating temperatures and reduce the electrical stresses.

The second type of duty cycle is a direct result of the function of a display, i.e., to display any of a variety of alpha-numeric characters. Different segments and different numbers of segments are used to display the various characters. For example, in the common 7-segment numeric display used in clocks, calculators, etc., one segment is used in only 4 out of the 10 possible digits (0 through 9), another is used in 9 out of the 10 digits. Assuming an equal probability of displaying any given digit, the individual LED segments will see duty cycles between 40% and 90%, with an average of 69%.

A third type of duty cycling is due to the nearly universal practice of multiplexing multi-digit displays. When this is done, each digit of an n-digit display is powered 1/n (or less) of the time. For example, a ten digit calculator display is usually multiplexed so that each digit is on 1/10 or 10% of the time.

As a result of these effects and because several of the dominant degradation and failure mechanisms occur only with power applied, the typical LED chip in a character display will often survive more <u>system hours</u> of operation than its discretely packaged counterpart. When actual chip "on-time" is considered, however, the reliability of the LED character display and discrete LED are comparable.

Working to counteract this apparent reliability advantage is a decrease in package reliability due to increased mechanical complexity and size. Even so, the failure rate of LED displays is expected to increase slowly with complexity.

2.2.3 Laser Diodes

Laser diodes are constructed in a manner simi.ar to that of LEDs; both are fabricated from a similar epitaxially grown structure. A laser diode has a cavity with optical feedback; thus, the stimulated emission is dominant and the electron-hole pairs recombine to produce coherent photon emissions. As a result, the light coupled into a fiber from a laser diode will be one to two orders of magnitude greater than from an LED.

Laser diodes exhibit many of the failure modes and mechanisms found in other semiconductor diodes, e.g., bond problems, contamination problems, and package-related problems. In addition, there are several relatively unique reliability problems. As with LEDs, only the less familiar failure mechanisms will be discussed here.

Facet or surface damage is a lasing-related degradation mechanism and therefore is not observed in LEDs. The damage is caused by operation of the laser diode at high optical power densities. This degradation can be suppressed by operating the device at moderate power levels (5 mW per face) or by properly coating the emitting surface to enhance its optical characteristics.

Dark line defects (DLDs) and uniform degradation mechanisms are observed in laser diodes as well as LEDs. The causes are identical and the effects similar, i.e., a reduction in light output efficiency. Since these degradation mechanisms were previously discussed they will not be covered here.

It should be apparent from the above discussion that, with the exception of laser facet damage, failure mechanisms of laser diodes and light emitting diodes are nearly identical. (Since laser facet damage is an overstress-induced condition, it may be elminated by operating the device below the damage threshold level.) Because of this commonality of construction, operation, and failure mechanisms, it seems reasonable to

use the same failure rate model for both device types. This assumption is supported by the literature: Dixon and Hartman[1] showed that the uniform degradation was not lasing-related; Kawakami[2] et al. demonstrated that dark line defects were a bulk crystal problem which could be eliminated by carefully growing and processing the crystal. The apparently faster degradation in laser diodes is due to the higher operating temperatures in the laser and is not attributable to the lasing phenomenon itself.

2.2.4 Photodiodes

Photodiodes are light sensitive diodes whose reverse (leakage) current is a function of the amount of light incident upon the device. Two basic types of photodiodes are currently available: p-i-n photodiodes and avalanche photodiodes (APDs).

2.2.4.1 P-I-N Photodiodes

The operation of a p-i-n photodiode is illustrated schematically in Figure 2.2. "P-i-n" refers to the doping profile of the diodes; "p" refers

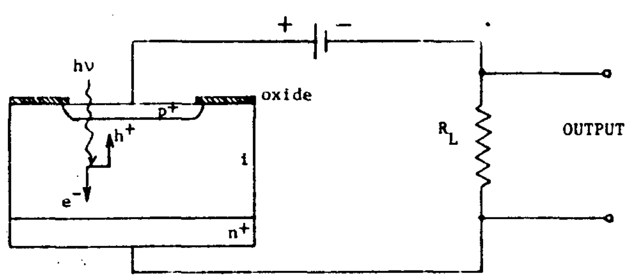


FIGURE 2.2 STRUCTURE OF A P-I-N PHOTODIODE

to the p-type electrode and "n" refers to the n-type doping of the other electrode, as in any diode. The "i" refers to the intrinsic (undoped)

1. Dixon, R.W., and R.L. Hartman (Bell Labs., Murray Hill, NJ). ACCELERATED AGING AND A UNIFORM MODE OF DEGRADATION IN (Al,Ga)As DOUBLE-HETEROSTRUCTURE LASERS. J. of Appl. Phys. 48, no. 8, Aug. 1977.

2. Kawakami, T., et al. Review of the Electrical Communication Laboratories, Vol. 26, no. 9-10. Sept. - Oct., 1978.

region between electrodes. The high resistivity of this region results in a large electrical field. A photon of sufficient energy absorbed into the i-region will interact with the crystal, generating an electron-hole pair. The strong electric field in this zone then sweeps the charge carriers out of the device where they contribute to the current through the external load resistor.

The shallow p-diffusion and thin oxides necessary to allow sufficient photon penetration leave the p-i-n photodiode particularly vulnerable to ionic contaminants. Under normal operating conditions, the voltage bias (up to 30 volts) causes ionic drift resulting in localized concentrations of charge which manifest themselves through degraded electrical parameters, particularly leakage (dark) current.

The very fast response time (0.1 to 10 nsec) of p-i-n photodiodes make them particularly attractive as detectors for high speed fiber optic data links. Principle disadvantages are its relatively high noise levels and extremely small output power.

2.2.4.2 Avalanche Photodiodes

The avalanche photodiode (APD) operates with an internal gain mechanism, thus supplying greater sensitivity and output power than the p-i-n structure. Also, the APD may offer a signal-to-noise ratio as much as 10dB better than a p-i-n photodiode. These benefits are obtained at the expense of slower response times and higher bias voltage requirements. Still, for many fiber optic systems the performance specification of the avalanche photodiode make it the preferred choice.

The principle underlying APD operation is impact ionization. If the electric field is sufficiently high, a free electron or hole can gain enough energy to free a bound electron. These ionized carriers can then cause further ionizations, leading to an avalanche of carriers.

The structure of a typical APD is shown in Figure 2.3. The depletion region is separated into a wide drift region (π) and a narrow multiplying region. Photons are absorbed into the drift region, while avalanche occurs in the multiplying region.

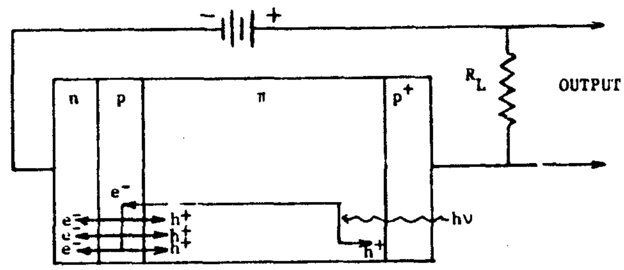


FIGURE 2.3: STRUCTURE OF AN AVALANCHE PHOTODIODE

In order to establish the field intensity necessary for avalanche multiplication, an APD is operated at very high reverse bias voltages, typically 200 to 500 volts. This requirement makes the device very susceptible to any voltage-accelerated failure mechanisms, particularly surface charge contamination problems and electrolytic corrosion reactions. As with most microelectronic components, high temperatures should also be avoided. As with other optoelectronic components, the failure rate of an avalanche photodiode exhibits an exponential (Arrhenius) temperature dependence with an equivalent activation energy, E_{ea}, of about 0.7eV.

2.2.5 Phototransistors

The phototransistor functions in a manner similar to a conventional transistor, the principle difference arising in the source of the base current (I_b). In a conventional transistor the base current is supplied directly by external circuitry whereas in a phototransistor the base current arises indirectly as a result of photon-induced ionization at the collector-base junction. The phototransistor has an advantage over the

photodiode in that the resulting photocurrent is amplified through the normal current gain function of a transistor. The current gain is achieved at the expense of response time, however. The speed of response of a phototransistor is limited by the capacitance of the collector-base junction, which in turn must be relatively large to achieve adequate sensitivity to light.

As with photodiodes, a primary contributor to unreliability is the problem of ionic contamination. Damage in phototransistors is often accelerated due to relatively high operating temperatures resulting from the greater power dissipation of these devices. To achieve maximum reliability it is particularly important to operate phototransistors at derated voltage, power, and temperature conditions.

Accelerated testing at elevated temperature has indicated an Arrhenius temperature dependence of failure rate with an equivalent activation energy of about 0.7eV. This is consistent with testing done on other semiconductor devices which are also susceptible to ionic contamination problems.

2.2.6 Photoresistors

A photoresistor is any of several types of bulk semiconductor devices whose conductance varies in proportion to the amount of light incident upon the device. As such, photoresistors are inherently linear in function and are susceptible to a variety of drift and degradation related problems. Photoresistors are seldom used in new designs, and are considered in this study only to the extent that they are used as detectors in optically coupled isolators.

2.2.7 Optoisolator or Optically Coupled Isolators (OCI)

An optoisolator is a hybrid-type assembly consisting of a light emitter and a light detector, separated by some transparent dielectric.

The optoisolator provides information transfer with total voltage and current isolation. For the purposes of this study, the only light source to be considered is the light-emitting diode (LED). Solid-state photodetectors considered include phototransistors, photodiodes, and photoresistors.

While the existing optoisolator reliability prediction model in MIL-HDBK-217 considers device complexity as a primary indicator of reliability, the data collected to support this program did not support such an assumption. It was determined that a much better indicator of reliability is the type of photo-sensor employed. The amount of circuitry between sensor and output proves to have little impact on overall device reliability. This result is consistent with the findings of a study done at NASA Goddard Space Flight Center. (See E. Thomas et al.)

The most common failure mode of OCI's is degradation of current transfer ratio (CTR). This degradation is traceable to two sources: the LED and the detector.

The LED degradation is identical to that observed in discrete-packaged devices. Temperature is the dominant accelerating stress, and a forward bias is required. Under conditions of reverse bias (especially at higher temperatures) another type of degradation is observed, namely excessive leakage currents in the phototransistor. This is due to the formation of a surface inversion layer at the junction.

In devices using diode detectors, the lower voltages and reduced power dissipation inhibit the surface problems observed in transistors--thus, the improved reliability of these types of devices.

Photoresistors operate at power levels intermediate between photodiodes and phototransistors. Dominant failure mechanisms relate to ionic contaminants and result in excess leakage currents or changes in resistance.

2.2.8 Optical Fibers

An optical fiber is any of several types of fine cylindrical dielectric materials which have the capability of "conducting" light internally along their length. Fibers have been manufactured which use several different "conduction" mechanisms, including total internal reflection, optical waveguides, and self-focusing fibers.

Early optical fibers were of the total internal reflection (TIR) type, the basis for transmission being total reflection at the interface between the fiber's cylindrical core and the layer of cladding material surrounding it. These fibers are available in both glass and plastic materials and exhibit relatively large attenuation (~1db/m).

Another type, the waveguide fiber, propagates light in a manner analagous to electromagnetic propagation in microwave waveguides. These fibers exhibit greater bandwidth and lower attenuation (~.01db/m) than the TIR type.

A separate class of fibers utilize a "self-focusing" property. The index of refraction decreases radially from the center of the core, causing light to be "focused" along the fiber.

Other types of optical fibers, such as fluid filled fibers, have been constructed but have not yet had any significant degree of commercial success and will not be considered in this study.

The three types of fibers listed above (TIR, waveguide and self-focusing) are similar in construction, despite differences in their theory of operation. Each consists of a transparent cylindrical core with refractive index n and a cladding material of index $n_2 < n_1$. Depending on the type of fiber, the core-cladding interface may be a step function or a gradual transition. The performance advantages of the graded index fiber make it the most popular choice for new design, particularly where bandwidth and attenuation are important design constraints. Due to the

similarity of construction of the several types of fibers, no significant reliability differences have been observed between the types. Thus, the following discussions will not distinguish between them.

Early applications of fiber optics were most commonly of the fiber bundle type: many fibers are bundled together and function as a single unit. Except in instances where the multiple redundancy of the bundle is a necessary feature, the relatively low bandwidth and high attenuation of bundles have precluded their use in new designs.

Since there is little interest in fiber bundles at the present time, this report will only discuss single-fiber types. It should be understood that the results and conclusions presented here may be directly extrapolated to fiber bundles.

The basic constituent of all but the most inexpensive optical fibers is glass. Glass is a stable material, being relatively immune to the various chemicals and ionic contaminants which have proven detrimental to the reliability of semiconductor devices. Also since no current flows through an optical fiber, the common voltage and current accelerated failure mechanisms are not a problem. As might be expected, the most common failure mechanisms are cracks and breaks.

The two predominant failure modes of an optical fiber are excessive attenuation (a degradation of light transmittion capabilities) and catastrophic failures due to fiber fracture. These conditions are discussed in detail in the following paragraphs.

Any fiber will exhibit a number of randomly located surface defects referred to as microcracks. These surface flaws act as localized stress intensifiers, causing fractures to occur at a lower stress than would be expected from the bulk properties of the glass. Moisture has been shown to reduce the strength of SiO bonds, resulting in still lower fracture stress. The effects of microcracks and moisture may be minimized by coating the fiber with an appropriate material. The coating usually consists of a thin

plastic primary layer and a thick plastic secondary layer. A graph showing the tensile strength of a glass fiber given coatings of different thicknesses is shown in Figure 2.4. The coating clearly increases fiber strength, as well as providing protection from moisture, abrasion and other environmental hazards.

Attenuation within an optical fiber may result from several causes, including microbending, thermally induced shifts of the absorption band, nuclear radiation, and others. While the causes are varied, the effects are similar: the ability of the fiber to transmit light is reduced. Graphs of fiber attenuation versus radiation dosage, time and wavelength are presented in Figures 2.5, 2.6, and 2.7, respectively. A graph of fiber attenuation versus temperature for two fiber types is presented in Figure 2.8.

Even with a coating material applied, a glass fiber is too fragile to be installed in any but the most benign conditions. For this reason, the optical fibers are usually placed in cables. An optical fiber cable having tensile reinforcement or strength members enables the cable to be drawn through conduits, held under high tension with low strain to the fiber and is sufficiently flexible to allow bending around relatively small radii.

The most important consideration in the design of the fiber optic cable is to prevent static fatigue of glass fibers. Static fatigue failures occur after a period of time at a constant load, due to the slow growth of flaws (i.e., microcracks).

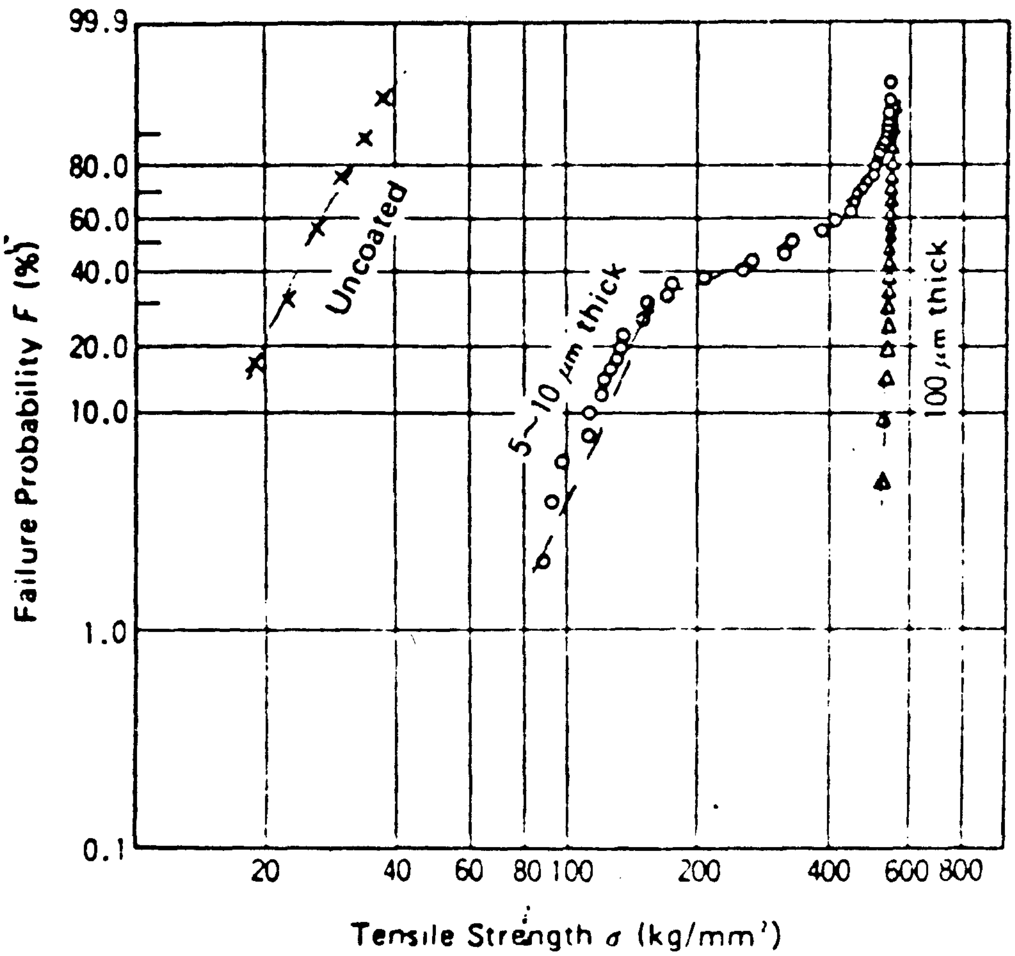
It has been shown (3,4,5) that the failure probability, $F(\sigma_a)$, of a glass fiber of length L subject to a tensile stress σ_a for time t is given by

$$F(\sigma_a) = 1 - \exp\left[-\left(\frac{L}{L_o}\right)\left(\frac{\sigma_a}{\sigma_o}\right)^m\left(\frac{t}{t_o}\right)^b\right]$$

3. Ritter, J.E., Jr., et al.
   J. of Appl. Phys., 49, (9), Sept. 1978.

4. Ritter, J.E., Jr.
   Fiber and Integrated Optics, Vol. 1, no. 4.

5. Olshansky, R., and R.D. Maurer.
   J. of Appl. Phys., Vol. 47, no. 10, Oct. 1976.



x : Uncoated

o : 5 ~ 10 μm thick polyurethane

Δ : 100 μm thick silicone resin

FIGURE 2.4: Effects of Coating Thickness on Tensile Strength of Optical Fibers.
Sakaguchi, S., and M. Nakahara. Review of the Electrical Communication Laboratories, Vol. 27, no. 3-4, March-April 1979.

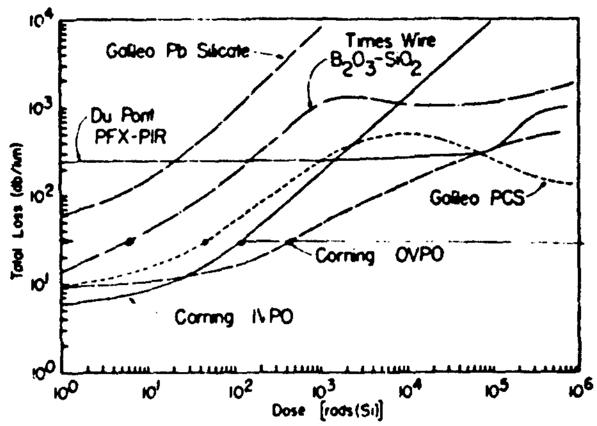


FIGURE 2.5: Total Optical Attenuation at 820 nm of Fiber-Optic Waveguides as a Function of Dosage during in situ "Co-irradiation". Friebele, E.J., et al. (U.S. Naval Res. Lab., Washington, DC). Laser Focus. Sept. 1978.

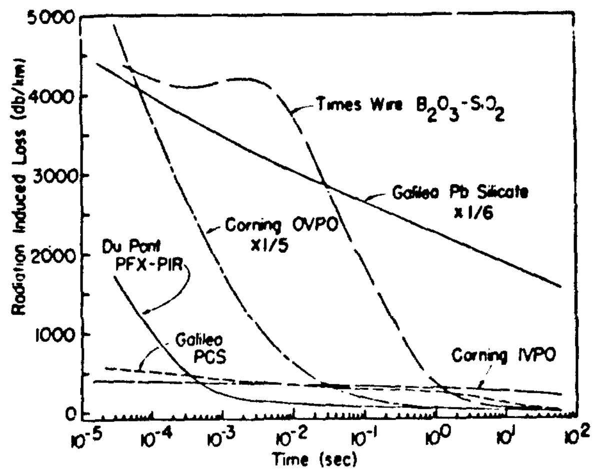


FIGURE 2.6: Radiation-Induced Optical Attenuation at 820 nm as a Function of Time Following a 3-ns, 3,700-rad dose of 0.5 megaelectronvolt electrons.
Friebele, E.J., et al. (U.S. Naval Res. Lab., Washington, DC). Laser Focus. Sept. 1978.

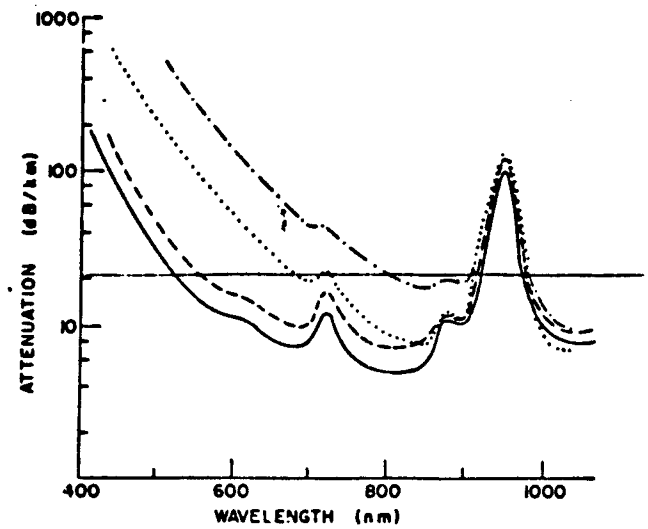


FIGURE 2.7: Change in Attenuation of a Multimode Optical Waveguide with Cumulative 14 Mev Neutron Irradiation: --- Unirradiated, --- 5.5 x 10^{10} n/cm^2, ...5.6 x 10^{11} n/cm^2 _._. 1.4 x 10^{12} n/cm^2.
Maurer, R.D., et al. Applied Optics, Vol. 12, no. 9, Sept. 1973.

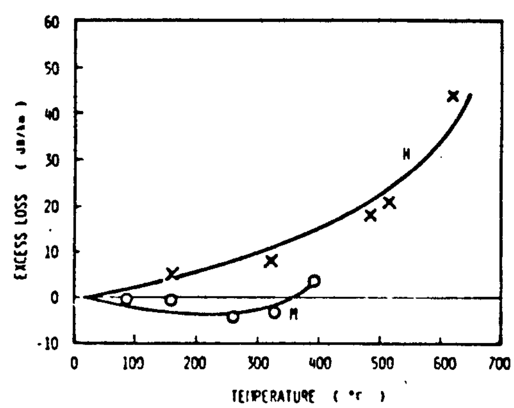


FIGURE 2.8: The Temperature Dependence of Optical Loss at 0.63µm for the Loose Coils of Fiber M: Multicomponent Glass Fiber H: High-Silica Glass Fiber.
Takahashi, S., and S. Shilata. J. of Non-Crystalline Solids 30, 1979.

The constants, t_o, L_o, σ_o, b and m, in the above equation may be determined experimentally by performing static fatigue experiments. Unfortunately, static fatigue experiments can be very tedious. Large numbers of samples must be broken at each value of applied stress σ_a to provide a reliable estimate of the parameters. An attractive alternative technique is called dynamic fatigue (3,4). It provides a much more efficient experimental procedure for determining the various constants.

The repeatability of experimentally determined stress constants is poor for reasons not fully understood. As a result, one manufacturer of fiber optic cables presently recommends that "not more than 20% of the fiber's screened strength be used for zero failure probability over a 20 year life span."

It is noted that the strength distribution of an optical fiber does not always exhibit a single mode; a bimodal or trimodal distribution may be found in a high strength optical fiber (6,7).

It is the responsibility of the cable designer to package the fibers into a cable so as to prevent excessive stressing of the fiber, both during and subsequent to installation. Several construction techniques are commonly employed to achieve this.

Strength members composed of material exhibiting low thermal expansion coefficients and very high tensile strength are integrated into the cable assembly. The most common material is Kevlar, although certain metal alloys are also available.

Another technique often used to reduce stress on the optical fibers is to wind the fibers helically (i.e., in a spiral) around a central "core". This prevents stress on the cable from being transmitted directly to the fibers; the fiber acts somewhat like a coil spring.

6. Tariyal, B.K., and D. Kalish.
   Material Science and Engineering, 27, 1977.

7. Sakaguchi, S., and M. Nakahara.
   Review of the Electrical Communication Laboratories, Vol. 27, no. 3-4, March-April 1979.

In cables intended for high-vibration environments, the fibers are often embedded in a layer of polyurethane or similar material in order to dampen any vibration and to prevent abrasion which could result if the fibers were allowed to come in contact with the cable material or with each other.

The importance of proper cabling is demonstrated by analysis of the only reported problem occurring with a field installed fiber optic cable. In this instance, a cable running outdoors above ground between two buildings was "failed" due to excessive attenuation only several months after being installed. It was discovered that the loss in the fibers was extremely dependent upon the ambient temperature. The particular cable was constructed with the fibers running parallel to the axis of the cable.

Failure analysis determined that the construction of the cable resulted in excessive strain to the fibers as a result of thermal expansion of the cable. When the cable was replaced with one using a more thermally stable strength member and helically wound fibers, the problem disappeared.

The manufacturer of the cable was not at fault, since the malfunctioning cable was intended for "indoor" use only. The example is mentioned only to show the importance of using a cable which is appropriate for the intended application.

2.2.9 Fiber Optic Connectors

As with cables, only single fiber types will be considered.

The fiber optic connector provides the mechanical alignment necessary for proper light coupling, whether it be emitter-to-fiber, fiber-to-detector, or fiber-to-fiber. (The "welding" of two fibers to produce a single fiber is designated a connection and will not be addressed in this report.) Basic characteristics of a well-designed fiber optic connector include:

- Easy assembly with simple tools
- Firm structure to withstand repeated mating cycles
- Good environmental characteristics
- Good alignment accuracy without adjustment
- Light weight and reasonable size.

Since fiber optic connectors transmit no electrical power, all failure modes of these components relate to mechanical anomalies. The major failure mode of fiber optic connectors is excessive attenuation due to inadequate alignment. Alignment is achieved by any of several techniques, including jeweled ferrules, precision sleeves, and a 4-rod alignment technique. The limited data available during this study would not permit a comparison of the reliability of the several techniques. (The only fiber optic connectors identified as requiring field replacement are no longer in production. They were replaced because inadequate strain relief resulted in fiber breakage during connector mating-demating cycles.)

Several reliability-related complaints have been made about connectors by people in industry. The extremely small number of mating-cycles-to-failure was a common complaint; in some instances as few as 5 cycles caused degradation sufficient to require replacements.

Another complaint pertained to alignment of the connector. In order to achieve optimum coupling it was necessary to rotate one half of the connector relative to the other. This manual "tweaking" operation may be tolerated on small systems but would prove impractical and expensive in a very large system.

It should be pointed out that no industry standards for optical fiber diameter exists. As a result, connector manufacturers must design a connector to function acceptably over a range of fiber diameters, instead of designing one which is optimized for a specific fiber diameter. It has been stated that major improvements in conectors must await the acceptance of standard diameters for optical fibers.

2.3 Data Collection

The modification of current prediction models or the development of new prediction techniques should be based upon reliability data. These types of modeling activities require extensive reliability data resources since models derived from limited data will reflect the characteristics of only that information.

The requirement for vast quantities of reliability data for model development necessitated the initiation of a data collection effort to supplement the existing information. This data collection effort included a literature search for published information in journals, technical reports, handbooks, etc., and a survey of commercial, industrial and government organizations for reliability data on fiber optic components and assemblies.

2.3.1 Data Survey

Numerous potential data sources were identifed by the results of a RAC Fiber Optics Reliability Survey which was conducted in the winter of 1979-80. The survey presented a series of questions designed to determine the extent to which fiber optic components and assemblies were being employed in new equipment designs and the experiences which had been accumulated with these devices. The survey forms were sent to over 10,000 individuals in various commercial, industrial and government organizations. Over 100 of the survey respondents indicated that they were or would be utilizing fiber optics in equipment designs. Each of these organizations was contacted to acquire its reliability experiences. Discussions with individuals within these organizations resulted in references to other potential data sources.

Additional requests were forwarded to all fiber optic and optoelectronic component manufacturers to obtain device construction and test information. In total, slightly over 300 organizations were contacted in the data collection effort.

Approximately 20% of the organizations contacted during the data collection effort submitted information to RAC. A primary concern of the majority of contributors was the proprietary nature of the information and the desire to remain anonymous. For this reason, none of the data contributors in this study will be identified.

The types of information collected include life test, accelerated life test, screening, burn-in, reliability demonstration, field experience, device characterization and device malfunction data. These data encompass all fiber optic system components, including LEDs, LED displays, laser diodes, phototransistors, photodiodes, fiber optic cables, fiber optic connectors, and optoisolators.

Concurrent with model development activities, field data were collected on optoelectronic and fiber optic components. These data items were not employed during model development, as they were intended to be used in the model validation activities to demonstrate that the proposed models are accurate for data points other than those used to derive the model.

Table 2.1 presents a summary of the data collected for the model development and model verification activities by device type.

TABLE 2.1
DATA SUMMARY BY PART TYPE

Component Type	Model Development		Model Verification	
	Part Hours	#Failed	Part Hours	#Failed
Discrete LED	3593×10^6	449	2084×10^6	134
LED Displays	1361×10^6	274	944×10^6	91
Laser Diodes	0.012×10^6	0		
Optoisolators	190×10^6	266	305×10^6	94
Phototransistors	7.08×10^6	0	10.9×10^6	4
Photodiodes (all types)	1.76×10^6	0	3.63×10^6	0
Fiber Optic Cables				
Single Fiber (fiber km hrs.)	2.88×10^6	1 (secondary)	0.32×10^6	0
Fiber Bundles (km hrs.)	2320	0	-	-
Fiber Optic Connectors				
Single Fiber	2.92×10^6	1 (secondary)	0.5×10^6	0
Fiber Bundles	10.1×10^6	3 (secondary)	-	-

2.4 Data Reduction and Analysis

The development of a viable prediction methodology for fiber optic components involves identifying and quantifying all significant reliability parameters and factors through an in-depth evaluation and analysis of accumulated reliability experience data and information. This section outlines the approaches, conventions, and assumptions used in the reduction and analysis of the data.

2.4.1 Data Reduction

To maximize the utility of the data collected, it was necessary to make several assumptions regarding failure criteria and the probability distribution of component times-to-failure.

Due to the problems involved with trying to establish a uniform field failure criterion for degraded components, it was decided that for purposes of this study a degradational failure occurred when the system or assembly employing the component ceased to function satisfactorily. While this assumption makes the time-to-failure circuit dependent and, in some cases, a matter of personal judgment, it is assumed that the field usage data collected for this study is statistically representative of the total population, and therefore the failure criteria used by the data sources are assumed to be "typical" of those used throughout the industry. Thus degradational failures are not considered separately but are counted as failures whenever inadequate system operation resulted. This assumption simplifies calculations while allowing for realistic predictions of the frequency of maintenance actions due to improper or inadequate operation of a component.

While several different probability distributions have been used to model the times-to-failure of semiconductor components, the prediction models derived in this study are based on an exponential distribution with its underlying constant failure rate assumption. The several reasons for this are as follows:

o Conservative Model

It has been suggested that some semiconductors exhibit a decreasing hazard rate with time. If true, this would make an exponential (constant failure rate) model a conservative or pessimistic one, especially if the model is based on data from the early life (i.e., warranty period) of the components.

o Maximum Data Utility

If any distribution other than an exponential is assumed, the parameters of the distribution must be determined by analysis of cumulative time-to-failure data. This detailed information is seldom available. The exponential distribution allows population parameter estimates to be made knowing only total part operating hours and total number of failures.

o Accuracy

When developing models as generic as those employed in MIL-HDBK-217 (encompassing a family of parts, in a general environment with a general quality level) any improvement in model accuracy resulting from the use of another, more complex, distribution would probably be insignificant when compared to the "noise" in the data.

o Precedent

The exponential assumption is currently used for the semiconductor reliability prediction models of MIL-HDBK-217.

o Simplicity

The mean time between failures (MTBF) of a system whose components exhibit constant failure rates is itself constant, whereas for a system

made up of components having non-constant failure rates, the system MTBF will be time-dependent and therefore undefined unless a particular mission time is specified.

For the above-mentioned reasons, the reliability prediction models developed for this contract presume a time-independent failure rate.

2.4.2 Data Analysis

A prerequisite to the summarization of data was the identification of all parameters and factors influencing component reliability. In order to accomplish this in a timely manner, a task was defined at the beginning of the program whose goal was the reliability evaluation of various component types based solely on theoretical considerations. These theoretical studies served to identify important device and application parameters influencing component reliability, as well as suggesting a form for the final failure rate prediction model.

Reliability data accumulated on the various components used in fiber optic systems were then summarized by recording the previously identified key test and device descriptors and entering them into an automated data base for subsequent analysis.

Data on various optoelectronic components were collected from a number of sources, both military and commercial. Since a number of data contributors submitted proprietary information, no mention of data sources will be made in this report.

Because fiber optics is a relatively new technology, and since much of the available field data is derived from warranty repair records, most of the data collected to support this modeling effort represents only the early life reliability of the devices considered. Consequently, very few wearout type failures were observed.

All data items received during the data collection efforts were reviewed for completeness of detail and examined for any inherent biases. Any data submitted which displayed obvious biases were not considered in this study. Those reports lacking sufficient detail were not considered until the necessary additional information was acquired.

When assuming a constant failure rate (i.e., exponential distribution), the failure rate, expressed in failures per million part hours, is calculated by dividing the total number of failures by the total millions of device hours. This single factor, referred to as the point estimate failure rate, does not completely characterize the reliability of a given device population.

The point estimate and the 60% Chi-square confidence interval failure rates were calculated for each of the data records. The Chi-sqaure statistic is used to identify a confidence interval around the point estimate failure rate. The 60% confidence interval is comprised of the lower-20% confidence and upper-80% confidence level points. A 60% confidence interval is that range of values around the estimate that would, with a 60% probability, include the actual mean of an infinite sample of the devices tested. These failure values are calculated as follows:

$$\text{Lower-20\% confidence point} = \frac{\chi^2\ (\alpha-1,\ 2r)}{2T}$$

$$\text{Point estimate} = \frac{r}{T}$$

$$\text{Upper-80\% confidence point} = \frac{\chi^2\ (\alpha,\ 2r+2)}{2T}$$

where:

r is the number of degrees of freedom equal to the number of failure

T is the total number of device hours (in millions of hours)

$\chi^2(\alpha)$ is the Chi-square value for the particular confidence level based on the number of degrees of freedom (determined from Chi-square Tables).

The use of the 60% confidence interval and point estimate failure rate provides a convenient method for weighting the various data records during model development analysis. The significance of the data record increases as the confidence interval points approach the point estimate value. Only the upper-80% confidence level failure rate was calculated for those data records with zero failures.

2.4.3 Statistical Modeling Technqiues

In order to identify and evaluate the relationships between the various reliability considerations which are defined by the data, various statistical analysis techniques were employed. The techniques which were applicable to the derivation of the reliability prediction model are briefly reviewed in the following paragraphs.

Stepwise Multiple Linear Regression Analysis. The stepwise multiple linear regression analysis routine assumes a preliminary model of the form:

$$Y' = b_o + b_1X_1 + b_2X_2 + \ldots b_iX_i$$

where Y' is the resultant dependent variable; X_1, $X_2 \ldots X_i$ are the independent variables which are thought to influence the value of Y'; and b_1, $b_2 \ldots b_i$ are the coefficients which will be found by the regression.

To perform a regression, a number of data points, each consisting of a known Y and its corresponding X variables, are required. A proper regression also requires that the X variables be nearly independent and that there are many more data points than X variables.

The regression technique first computes a correlation matrix comparing all the X variables to one another as well as to the observed Y. This matrix serves to identify any nonindependent X variables (except those which are a function of two or more other X variables) and is also

used to compute the relative correlation of the Y variable to each of the X variables.

The analysis orders the X variables according to their relative correlation with the Y variables. Considering the first X variable and the Y variable, b_o and b_1 are computed such that the sum of the squares of $(Y-Y')$ will be a minimum. The second X variable is then considered in the computation of b_o, b_1 and b_2 such that the sum of the squares of $(Y-Y')$ will again be minimum.

If the improvement in the estimate afforded by the inclusion of this second variable is significant with respect to a given confidence level, the variable is accepted as part of the model and regression continues by considering a third variable.

If considering the second variable does not result in a significant improvement, the model remains

$$Y = b_o + b_1 X_1 \quad .$$

Whenever a new variable is included in the fitted model, all previously included variables are retested for significance, given that the new variable is in the model.

The regression continues until all of the signficant X variables have been identified and their corresponding b coefficients have been calculated.

Several measures of the "goodness of fit" of the model to the observed data are generally available for a regression model.[8] A review of the more important of these measures is presented as follows.

8. N. Draper and H. Smith, Applied Regression Analysis (John Wiley & Sons, Inc., 1966).

R^2 - Multiple Correlation Coefficient. This is probably the single most useful "goodness of fit" measure. The R^2 value is the ratio of the sum of the squares of the variance explained by the regression to the sum of the squares of the variance in the observed data. An R^2 value of 100% is the ideal result.

Critical F. The critical F is the value from the F Table corresponding to the degrees of freedom of the model and the difference between the number of data points and the number of b coefficients. This number may be used to test the significance of each variable as it is considered for addition to or deletion from the model. The calculated F value for a regression is the quotient of the mean square due to regression and the mean square due to residual variation. If the calculated F value is greater than the critical F value at the given significance level, it can be said that the last variable does not equal zero with a confidence of $1 - \alpha$, where α is the level of significance.

Estimated Standard Error of b_i. The estimated standard error of each b_i is the square root of the estimate variance. This value may be used to establish confidence intervals around the respective b_i's.

Standard Error of Estimate(S). The standard error of estimate is the square root of the residual mean square (the estimate of the variance about the regression). A small S value indicates a good fit, providing there are few repeats and many degrees of freedom for the error remaining.

Residuals. A residual is the difference between the observed and calculated Y values for each data point ($Y_i - \acute{Y}_i$). The residual may be plotted vs. one of the variables in order to evaluate patterns or trends. This may lead to the identification of new variables or transformations of current variables.

Fischer "F" Test. The complexities associated with the characteristics of optoelectronics make it impractical to consider every possible variable when attempting to model the reliability of a device. As a result, the variables to be included are constrained to those which will have the most significant impact upon the reliability. The F-test technique can be employed to determine if any significant variables have been neglected. This may be accomplished by segregating the data resources into groups with the same set of significant variables. Applying the F-test to each of these groups will determine if there is sufficient statistical evidence to conclude that a data point or a set of data points comes from a population with a mean which is not the same as the rest of the data. While a few outliers may be expected, an additional variable should be sought if a large percentage of any group is found to be divergent.

Curve Fit Analysis Technique. A series of curve fit programs are available for establishing the mathematical relationship between dependent and independent variable pairs in a given data set. These techniques provide a least squares curve fit of the data points to various types of expressions, including linear, exponential, power, and hyperbolic functions. The output of these programs express the dependent variable (Y) in terms of the independent variable (X) and two coefficients (A,B). In addition to the values of the coefficeints A and B, the output provides an index of determination for each function which represents the "goodness-of-fit" of the expression to the data points.

2.4.4 Empirical Modeling Procedure

The approach utilized in the development of the model format combined the relationships, as suggested by the theoretical analyses and the literature, with the statistical analysis techniques and data resources. The basic methodology employed in the model development is illustrated in Figure 2.9.

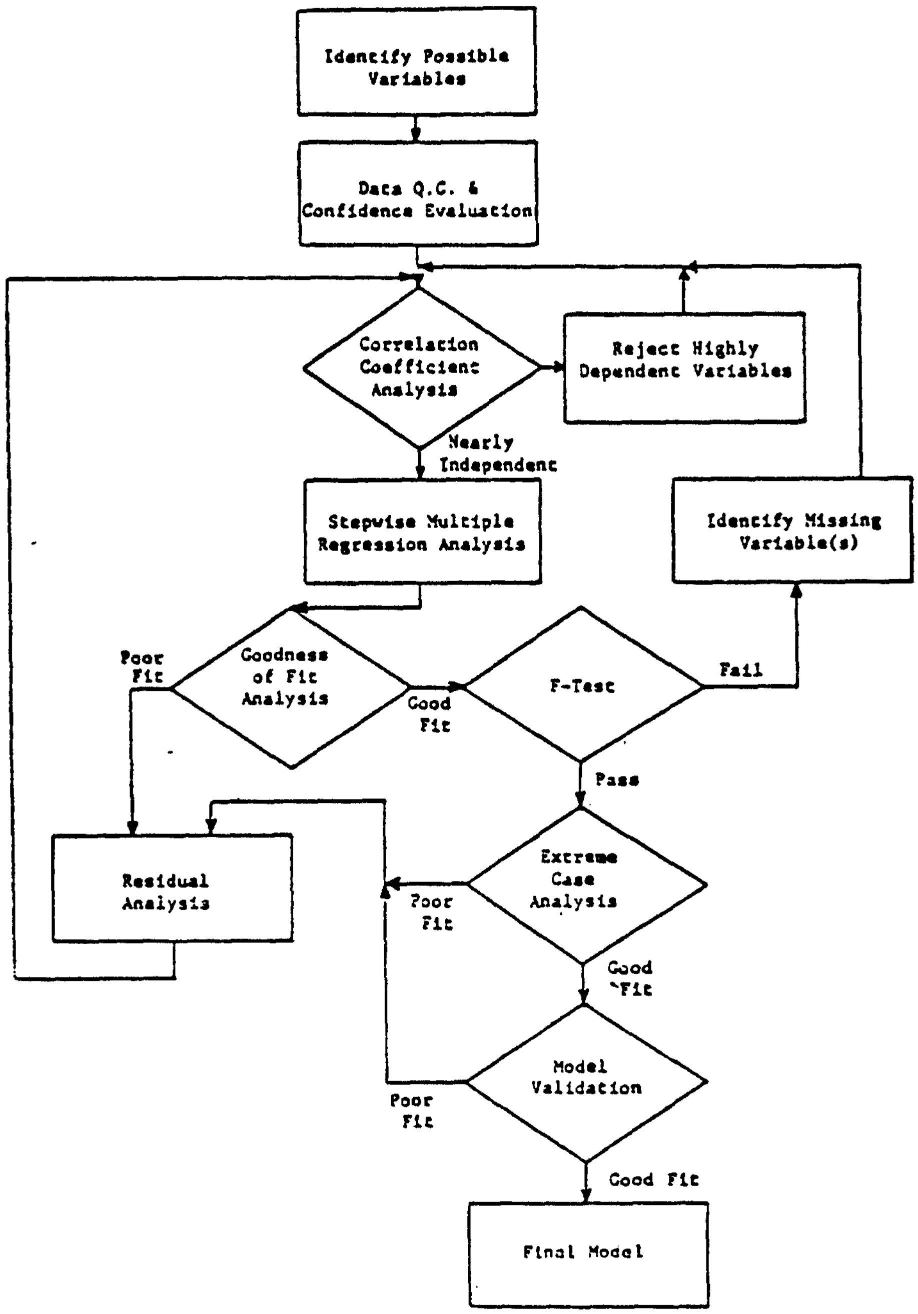


FIGURE 2.9: EMPIRICAL MODEL APPROACH METHODOLOGY

The technique represented in Figure 2.9 can be briefly explained as follows:

Identify Possible Variables. As previously indicated, the variables considered in the analysis were identified during the data collection activities based upon the parameters suggested by the theoretical modeling effort and the literature.

Data Quality Control and Confidence Evaluation. The data quality control was established in the data collection activities. Only unbiased data which identifed all variables of concern in this study program were considered. The confidence for each data point was evaluated using Chi-square techniques. These confidence intervals were employed as figures of merit when evaluating the impact of each data point during the subsequent statistical analyses.

Correlation Analysis. To perform a proper regression analysis, all of the selected variables must have a low interdependence. The regression program employed in this study offered a correlation coefficent matrix as a preliminary option in the regression. This matrix indicated the degree to which each variable was related to the other. Those variable pairs which exhibited high correlation coefficients were reviewed to either combine the variable or eliminate one of the variables from the regression. The magnitude of the various term coefficients provided a useful means of determining which parameters had the greatest impact upon reliability.

Stepwise Multiple Regression Analysis. This technique has been described in Section 2.4.3. The objective is to compute the coefficients of the assumed form of the model in a least squares fit to the data employing only those variables which are significant to a given confidence level. The limitation of the technique is the presumption of the model form. The regression does not suggest the optimal form of the model but rather computes the coefficients for the standard additive form. Multiplicative or other model forms can only be achieved by transforming variables in the regression.

"Good Fit" Tests. The goodness-of-fit" techniques including residual analysis, standard error, R^2 and F-test were employed to determine if the models were realistic with respect to the data. These tests identified the need for additional variables and suggested those variables which should be transformed to result in better model fit to the data.

Model Validation. The validation process consisted of tests at extreme and nominal parameter values. Predictions were made using the models for values of the parameters which are beyond the ranges found in the data. While there were not any data for comparison with the prediction, the predictions were used to reveal any combination of values for which the prediction "blew up" or predicted a failure rate which was theoretically inconsistent or intuitively wrong. Predictions were also made for data not employed in the model development to determine if the models accurately reflected the reliability of data other than that used to develop model parameters.

Quality levels for semiconductor optoelectronic devices have been established and are similar to those of other discrete semiconductor components. The availability and usage of high reliability optoelectronic parts is extremely limited, however. The vast majority of the data collected for this study represents plastic encapsulated commercial quality parts. As such, the accuracy of the π_Q factors for these models could neither be verified nor disputed. Since they are consistent with the quality factors used in other discrete semiconductor models, the relative magnitudes of the factors were left unchanged in the proposed models.

Of the many application environment categories defined in MIL-HDBK-217, only a few have employed fiber optic systems. The data used in support of this study effort is predominantly based on systems deployed in ground fixed (GF) and ground benign (GB) application environments. As a result, no empirical means of checking the existing π_E factors was available. The models were derived by assuming the correctness of the existing factors. Near the end of this effort, the results of a recently

completed study by Burt Kremp of Martin Marietta Aerospace to revise the environmental factors of MIL-HDBK-217 were made available. These newly derived factors were checked for compatibility with the proposed optoelectronic models. No bias could be detected in the model as a result of the new factors. The non-operating factors developed by Martin Marietta could not be checked explicitly due to lack of data of this type.

SECTION 3
RELIABILITY PREDICTION MODELS

This section presents the proposed reliability prediction models and supporting information for optoelectronic and fiber optic components. These recommended modifications to the existing MIL-HDBK-217C model are the result of the analyses performed on the extensive data base compiled during this study. The proposed models are presented in 3.2 using a format and numbering scheme consistent with their intended location in MIL-HDBK-217C.

3.1 Background Discussion

The reliability prediction models developed for this study presume a time-independent failure rate. As such, the following general model is proposed for all semiconductor devices included within the scope of this contract, including light emitting diodes (LEDs), light emitting diode displays, optoisolators, laser diodes, phototransistors, and photodiodes.

$$\lambda_p = \lambda_b \pi_T \pi_E \pi_Q$$

where λ_p = predicted failure rate

λ_b = base failure rate

π_T = temperature dependent factor

π_E = application environment factor

π_Q = device quality level factor

The currently employed prediction models of MIL-HDBK-217C for LED devices and optoisolators are of the form

$$\lambda_p = \lambda_b \pi_C \pi_E \pi_Q$$

where π_C = device complexity factor
(all others same as above)

The base failure rate term (λ_b) for the present model in MIL-HDBK-217C is based on a complex exponential equation requiring a number of device parameters which do not always appear on vendors' specification sheets. Also, since derating temperature is a key parameter in that equation, the base failure rate is dependent upon the way a particular vendor chooses to derate its components. As a result, essentially identical devices from different vendors exhibited different base failure rates. This approach was considered unacceptable for the proposed models.

A tabulated set of complexity factors (π_C) is used in the existing model to account for differences in device types, as well as various levels of complexity within a given device type. This approach was considered unacceptable, since the term "complexity factor" is inappropriate when discussing the reliability differences between discrete LEDs and optoisolators. The two devices differ by more than just level of complexity.

Also, complexity has relatively little impact on the overall reliability of some devices (i.e., optoisolators). Thus, while complexity may be an important reliability-influencing factor for some devices, it does not have universal applicability.

For these reasons, the following modifications have been developed and incorporated into the proposed reliability prediction models:

- A new base failure rate descriptor was established. The values are tabulated according to device family and specific type. The base failure rate table of the proposed model is similar to the table of complexity factors employed in the existing model. The individual entries in the table were derived or interpolated from the data collected, then checked to insure compatibility with theoretical and intuitive considerations. Revisions were performed as necessary to provide a set of base failure rate values which could be validated both empirically and theoretically.

- A new parameter, π_T, was identified to account for the reliability impact of temperature on optoelectronic devices. This factor is based on an Arrhenius-type equation having an activation energy of 0.7eV. (Theoretical investigations disclosed that all semiconductor optoelectronic devices exhibited an exponential temperature dependent failure rate, with an equivalent activation energy of about 0.7eV.) The values of π_T have been tabulated for operating junction temperatures between $0^{\circ}C$ and $115^{\circ}C$. Parts operating at higher

temperatures are considered overstressed. No data was available for operation of optoelectronic components below $0^{o}C$. The tabulated π_T values are presented in increments of $5^{o}C$. For intermediate temperatures, values of π_T may be determined by using the equation

$$\pi_T = 8.01 \times 10^{12} \exp\left[-\frac{8111}{T_J+273}\right]$$

where T_J = operating junction temperature in ^{o}C

For each device type a typical value of temperature rise above ambient is given. These "typical" values are to be used in those situations where insufficient data is available to permit determination of the actual junction temperature of a device. These "typical" values were derived by calculating the temperature rise above ambient for a large number of devices of each part type and then averaging the results.

These changes have resulted in the proposed models presented in Section 3.2. Comments on the proposed model follow:

Discrete LEDs

Discrete LEDs have been used for several years in very large quantities for a number of commercial applications. As a result, a large amount of data was available on these components. The model development activity employed a data base of nearly 4 billion part hours of field usage data. This provided an excellent foundation for development of an improved reliability prediction model for light emitting diodes as well as providing a reference point for evaluation/comparison with models for similar types of devices where less data were available.

While differences in failure rate were observed between LEDs of various colors, the limited information available on non-red LEDs would not permit any statistical significance to be attached to the difference. Consequently, no color distinctions are made in the prediction model.

Laser Diodes

While there is ample information in technical reports and other literature to support the use of the same reliability prediction model for both light-emitting diodes and laser diodes, the total lack of field data on laser diodes prevented verification of this theory. Lack of field data is considered indicative of new and immature technology components. As such, the development of a reliability prediction model seems inappropriate at this time. Current state-of-the-art laser diodes may be expected to have an operating life of 10^4 to 10^5 hours at moderate power levels at room temperature. (See Kressel et al.).[9]

LED Displays

The relative failure rates of the several types of LED displays are identical in both the existing and proposed models. The numbers were simply scaled to bring the model in line with observed failure rates. As before, the failure rate increased slower than the complexity, so that, for example, a 5-digit display has a failure rate 2.2 times that of a 1-digit display. Also, the data indicates that a one-digit LED character display exhibits a failure rate lower than that of a single discrete LED. This can be explained by recalling the previous discussion of duty cycling in displays. Also, displays are usually driven by digital signals, while discrete LEDs are driven by linear (analog) signals. The chances of spurious signals which could overstress the device are greater for the analog-driven devices.

Optoisolators

Analysis of optoisolator life test data and field failure rate information both lead to the conclusion that the type of light detector used has much more impact on reliability than does the complexity of the

9. Kressel, H. et al. (RCA Labs., Princeton, NJ).
RELIABILITY SEMICONDUCTOR LIGHT SOURCES FOR FIBER OPTICAL COMMUNICATIONS.
1975 International Electron Devices Meeting.

device (See E. Thomas).[10] As a result, the proposed optoisolator model uses detector type as a criterion for assigning base failure rates, λ_b.

The difference in reliability between a simple isolator and one containing a logic chip and output driver was within the "noise level" of the data; no statistical difference could be determined.

The proposed model will only accomodate optoisolators using phototransistors, photodiodes, and light sensitive resistors as detectors. Devices using photothyristors and other less common detectors were not included due to lack of data.

The proposed optoisolator reliability prediction model assumes the use of an LED as the light source.

Phototransistors and Photodiodes

Since no reliability prediction models for phototransistors and photodiodes exist in the current edition of MIL-HDBK-217C, no comparison of old and new models can be made. The relatively limited field data available on these devices preclude the development of complex prediction models. The models proposed here were developed through a "hybrid" approach, drawing heavily on both empirical data and theoretical considerations.

Fiber Optic Cables and Connectors

Fiber optic cables and connectors represent a new and dynamic technology. Industry standards are slow in coming, technologies are often immature, and actual field data is very limited.

10. Thomas, E.F., and R.J. Anstead (NASA, Goddard SFC, Quality Assurance Div., Greenbelt, MD).
THE DEGRADATION CHARACTERISTICS AND MECHANISMS OF AN OPTICALLY COUPLED ISOLATOR.
Rept. no. FMR 743.90-001, July 28, 1975.

As a result, the development of full scale part stress reliability prediction models for fiber optic cables and connectors is impractical. Even if data could be collected in quantities sufficient to support a complex model, rapidly changing markets and technology would make the model obsolete in a matter of months. The development of full scale models should be attempted only after the fiber optic industry becomes stabilized. Signs of maturity are already present, with several industry standards already in various stages of preparation. It may be that several years from now, full scale reliability prediction models for fiber optic cables and connectors will not only be feasible but necessary due to the design of fiber optic data links into many new high reliabiity systems performing critical functions.

In the near term, in order to provide the manager or the engineer with a rough estimate of the reliability of fiber optic cables and connectors, a point estimate failure rate for each has been provided for inclusion in the "Miscellaneous Parts" Section 2.14 of MIL-HDBK-217. The point estimates were established after considering the limited amount of data which was available, in conjunction with life test results and discussions with manufacturers and users in industry. Note that the failure rate for single fibers is expressed in terms of failures per fiber per unit length per unit time; or failures per million fiber•km•hrs. Failure rates for fiber bundles are given in terms of failures per million km•hrs.

3.2 Proposed Models

MIL-HDBK-217 parapragh numbering is used below for the proposed models.

2.2.10 Opto-electronic Semiconductor Devices, Group X.

SPECIFICATION	DESCRIPTION
MIL-S-19500	Light Emitting Diodes (LED)
MIL-S-19500	Opto-electronic Coupler (Isolator)
None	LED Alpha-numeric Display
	Phototransistor
	Photodiode

The part failure rate model, λ_p, is:

$$\lambda_p = \lambda_b \pi_T \pi_E \pi_Q \text{ failures}/10^6 \text{ hours}$$

where

λ_b = base failure rate in failures/10^6 hrs., Table 2.2.10-4
π_T = temperature factor, Table 2.2.10-3
π_E = environmental factor, Table 2.2.10-1
π_Q = quality factor, Table 2.2.10-2

TABLE 2.2.10-1
π_E, ENVIRONMENTAL FACTOR

Environment	π_E
G_B	1
S_F	1
G_F	2
A_{IT}	2.8
A_{IF}	5.6
N_S	4
G_M	4
N_U	5
A_{UT}	4.2
A_{UF}	8.4
M_L	10

TABLE 2.2.10-2
π_Q, QUALITY FACTOR

Quality Level	π_Q
JANTXV	0.01
JANTX	0.02
JAN	0.1
LOWER*	0.5
PLASTIC**	1.0

*Applies to all hermetic packaged alpha-numeric displays and to NON-JAN hermetic packaged LED's and isolators.
**Applies to all devices encapsulated with organic materials.

TABLE 2.2.10-3
OPTO-ELECTRONIC SEMICONDUCTOR DEVICE
TEMPERATURE FACTOR π_T

T_J (^{o}C)	π_T
0	1.0
5	1.7
10	2.9
15	4.7
20	7.6
25	12
30	19
35	29
40	45
45	67
50	100
55	150
60	210
65	300
70	430
75	600
80	840
85	1200
90	1500
95	2100
100	2900
105	3800
110	5100
115	6700

$$\pi_T = 8.01 \times 10^{12} \exp \left[-\frac{8111}{T_J + 273} \right]$$

where T is operating junction temperature in ^{o}C

T_J = junction temperature

T_J may be calculated by using the equation

$$T_J = T_C + P_D \, \theta_{JC}$$

where

T_C = device case temperature
P_D = power dissipated by device
θ_{JC} = junction to case thermal resistance of package

If information is not available to use the equation above, use the following assumptions (T_A = ambient temperature)

Discrete LED	$T_J = T_A + 20^{o}C$
LED Display	$T_J = T_A + 30^{o}C$
Phototransistor	$T_J = T_A + 30^{o}C$
Photodiode	$T_J = T_A + 15^{o}C$
Single Isolators	
Photodiode Detector	$T_J = T_A + 15^{o}C$
Phototransistor Detector	$T_J = T_A + 20^{o}C$
Photoresistor Detector	$T_J = T_A + 20^{o}C$
Dual Isolators	
Photodiode Detector	$T_J = T_A + 20^{o}C$
Phototransistor Detector	$T_J = T_A + 30^{o}C$
Photoresistor Detector	$T_J = T_A + 30^{o}C$

TABLE 2.2.10-4

OPTO-ELECTRONIC SEMICONDUCTOR DEVICE

BASE FAILURE RATE, λ_b, IN FAILURES PER 10^6 HOURS

Device	λ_b	Device	λ_b
Single LED	.00065	Alpha-Numeric Displays*	
Single Isolators		1 character	.00050
		1 character w/logic chip	.00068
Photodiode Detector	.0010	2 character	.00071
Phototransistor Detector	.0055	2 character w/logic chip	.00089
Light Sensitive Resistor	.0025	3 character	.00088
Dual Isolators		3 character w/logic chip	.0011
Photodiode Detector	.0015	4 character	.0010
Phototransistor Detector	.0074	5 character	.0011
Light Sensitive Resistor	.0040	6 character	.0012
		7 character	.0013
Phototransistor	.0015	8 character	.0014
		9 character	.0015
Photodiode	.0011	10 character	.0016

*The number of characters in a display is the number of characters contained in a single sealed package. For example, a 4 character display comprising 4 separately packaged single characters mounted together would be [illegible]-one character displays, not 1-four character display.

2.14 MISCELLANEOUS PARTS

TABLE 2.14-1
FAILURE RATES FOR MISCELLANEOUS PARTS (FAILURES/10^6 HOURS)

Part Type	Specification	Failure Rate
Vibrators	MIL-V-95	
60-cycle		15.0
120-cycle		20.0
400-cycle		40.0
Quartz Crystals	MIL-C-3098	0.2
Fuses		0.10
Lamps		
Neon		0.20
Incandescent		1.00
Fiber Optic Cables (single fiber types only)		0.1 (per fiber·km)
Single Fiber Optic Connectors*		0.1
Meters	MIL-M-10304	10.0
Circuit Breakers		2.0
Microwave elements (coaxial & waveguide)		
Attenuators (fixed and variable)**		
Fixed Elements (directional couplers, fixed stubs & cavities)		Negligible
Variable Elements (tuned stubs & tuned cavities)		0.1

*Caution: Excessive mating-demating cycles may seriously degrade reliability

**Calculate same as Style RD resistor of Section 2.5

Supersedes page 2.14-1, 9 April 1979

3.3 Proposed Model Sample Calculations

Example 1

Description: A commercial quality plastic-encapsulated single optoisolator is used in a Ground, Benign application, junction temperature 65°C, the optoisolator uses a photodiode detector.

From Section 2.2.10

$$\lambda_p = \lambda_b \pi_T \pi_E \pi_Q$$

Table 2.2.10-4	Base Failure Rate λ_b = .0010
Table 2.2.10-3	Temperature Factor π_T = 300.
Table 2.2.10-1	Environmental Factor π_E = 1.0
Table 2.2.10-2	Quality Factor π_Q = 1.0

λ_p = 0.0010 (300) (1.0) (1.0) = 0.30 failures per million hours

Example 2

Description: A discrete, hermetic light emitting diode (LED) procured in accordance with MIL-S-19500 is used in an Airborne, Inhabited, Transport application environment. The device is a JAN quality part operating at a case temperature of 60°C. Package case-to-junction thermal resistance Θ_{JC} is 500 °C/watt. The device dissipates 50 mW.

The failure rate equation is:

$$\lambda_p = \lambda_b \pi_T \pi_E \pi_Q$$

Table 2.2.10-4	Discrete LED, Base Failure Rate $\lambda_b = 0.00065$
Table 2.2.10-2	Airborne Inhabited Transport Environment $\pi_E = 2.8$
Table 2.2.10-3	$T_C = 60^{\circ}C \quad P_D = .05w \quad \Theta_{JC} = 500\ ^{\circ}C/watt$
	$T_J = T_C + \Theta_{JC} P_D = 60 + 500(.05) = 60 + 25 = 85^{\circ}C$
	from Table 2.2.10-3, $\pi_T = 1200$
Table 2.2.10-2	JAN Quality Level $\pi_Q = 0.1$

Thus

$$\lambda_p = 0.00065\ (1200)(2.8)(0.1) = 0.22 \text{ failures per } 10^6 \text{ hours}$$

SECTION 4
MODEL VERIFICATION

Concurrent with model development activities, field data was collected for optoelectronic and fiber optic components. These data entries were not employed during model development, as they were intended to be used in the model validation activities to demonstrate that the proposed models are accurate for data points other than those used to derive the model.

4.1 Model Verification

The data entries are presented, along with observed and predicted failure rate values, by the following categories:

Table 4.1	Discrete LED Model Verification Data
Table 4.2	LED Display Model Verification Data
Table 4.3	Optoisolator Model Verification Data
Table 4.4	Phototransistor Model Verification Data
Table 4.5	Photodiode Model Verification Data

The data entries in each of the Tables presents the total number of device hours, the number of failures, the 60% Chi-square confidence interval and point estimate failure rates, and predicted failure rate values calculated using MIL-HDBK-217C (including Notice 1) and the proposed models.

In addition to the tabulated data, the correlation between the observed failure rates and the predicted failure using MIL-HDBK-217C and the proposed models are presented graphically for each of the data sets in Figures 4.1 through 4.8.

Discrete LEDs

Figures 4.1 and 4.2 present comparisons of predicted versus observed failure rates for discrete LEDs using the existing model and the proposed (new) model, respectively. Due to the source of the data used to verify the model, all data entries have the same predicted failure rate, i.e., same part type operating in same environment at the same temperature, and of the same quality level. As a result, the predicted failure rate is designated by a horizontal line as indicated in the figures.

A comparison of the two figures shows a noticeable improvement in the accuracy of the predictions done according to the new models. The predicted failure rates of the new model are far more representative of the observed values.

An important result may be drawn from these figures - the variability in observed failure rates for a set of parts under nominally identical circumstances. The observed failure rate data points vary over an order of magnitude. An analysis of these data show the distribution to be approximately normal (Gaussian), indicating random sampling errors from a population exhibiting a nominally constant failure rate.

Laser Diodes

For reasons previously discussed, no prediction model has been developed for laser diodes. State-of-the-art laser diodes have an expected lifetime of 10^4 to 10^5 hours. (It should be remembered that in reliability the concepts of failure rate and lifetime are disjoint and totally unrelated.)

LED Displays

Figures 4.3 and 4.4 present graphically the data presented in Table 4.2. It can be seen that the proposed LED Display reliability prediction model closely follows the observed failure rates for these components, whereas the existing model is excessively pessimistic.

Optoisolators

The existing and proposed optoisolator reliability prediction models are compared to observed field failure rate data in Figures 4.5 and 4.6, respectively.

Phototransistors and Photodiodes

A comparison of predicted and observed failure rates for phototransistors and photodiodes, as per the proposed models, is presented in Figure 4.7 and 4.8, respectively.

Fiber Optic Cables and Connectors

Since no field failures were reported, no validation of the point estimate failure rates for these components can be performed. The point estimates were established after considering the limited amount of data which was available, in conjunction with life test results and discussions with manufacturers and users in the industry.

TABLE 4.1

DISCRETE LED MODEL VERIFICATION DATA

Entry Number	Number Failed	Part Hours	Observed Failure Rate $\hat{\lambda}$	Chi-Square 60% Confidence Interval	λ_p Existing Model	λ_p Proposed Model
1	0	4,174,300	-	- - 0.39	1.46	0.14
2	0	2,260,700	-	- - 0.71	1.46	0.14
3	0	3,474,900	-	- - 0.46	1.46	0.14
4	0	1,617,200	-	- - 1.0	1.46	0.14
5	0	12,841,400	-	- - 0.13	1.46	0.14
6	12	203,104,200	0.059	0.045 - 0.078	1.46	0.14
7	1	45,125,600	0.022	0.004 - 0.067	1.46	0.14
8	0	284,700	-	- - 5.7	1.46	0.14
9	18	301,330,900	0.06	0.048 - 0.075	1.46	0.14
10	0	7,202,000	-	- - 0.22	1.46	0.14
11	9	3,689,400	2.43	1.74 - 3.4	1.46	0.14
12	5	106,538,900	0.047	0.029 - 0.075	1.46	0.14
13	0	5,402,800	-	- - 0.30	1.46	0.14
14	2	14,968,200	0.13	0.054 - 0.29	1.46	0.14
15	3	3,328,000	0.90	0.46 - 1.67	1.46	0.14
16	2	4,989,400	0.40	0.16 - 0.87	1.46	0.14
17	4	81,805,100	0.049	0.028 - 0.083	1.46	0.14
18	0	9,812,400	-	- - 0.16	1.46	0.14
19	0	7,215,000	-	- - 0.22	1.46	0.14
20	4	70,441,800	0.057	0.033 - 0.096	1.46	0.14
21	15	242,248,500	0.062	0.048 - 0.08	1.46	0.14
22	24	262,678,000	0.092	0.076 - 0.111	1.46	0.14
23	0	45,428,500	-	- - 0.035	1.46	0.14
24	5	40,838,200	0.12	0.076 - 0.20	1.46	0.14
25	0	3,996,200	-	- - 0.40	1.46	0.14
26	4	33,239,700	0.12	0.069 - 0.20	1.46	0.14
27	0	36,562,500	-	- - 0.044	1.46	0.14
28	3	8,299,200	0.36	0.18 - 0.67	1.46	0.14
29	16	130,880,100	0.12	0.096 - 0.16	1.46	0.14
30	2	29,718,000	0.067	0.027 - 0.145	1.46	0.14
31	2	83,851,300	0.024	0.01 - 0.052	1.46	0.14
32	1	17,191,200	0.058	0.012 - 0.18	1.46	0.14
33	0	10,445,500	-	- - 0.15	1.46	0.14
34	0	3,225,300	-	- - 0.50	1.46	0.14
35	1	20,018,700	0.05	0.01 - 0.13	1.46	0.14
36	0	4,457,700	-	- - 0.36	1.46	0.14
37	0	2,901,600	0	- - 0.56	1.46	0.14
38	0	2,291,900	-	- - 0.70	1.46	0.14
39	4	4,583,800	0.87	0.50 - 1.5	1.46	0.14
40	0	187,846,100	-	- - 0.009	1.46	0.14
41	0	18,842,200	-	- - 0.086	1.46	0.14

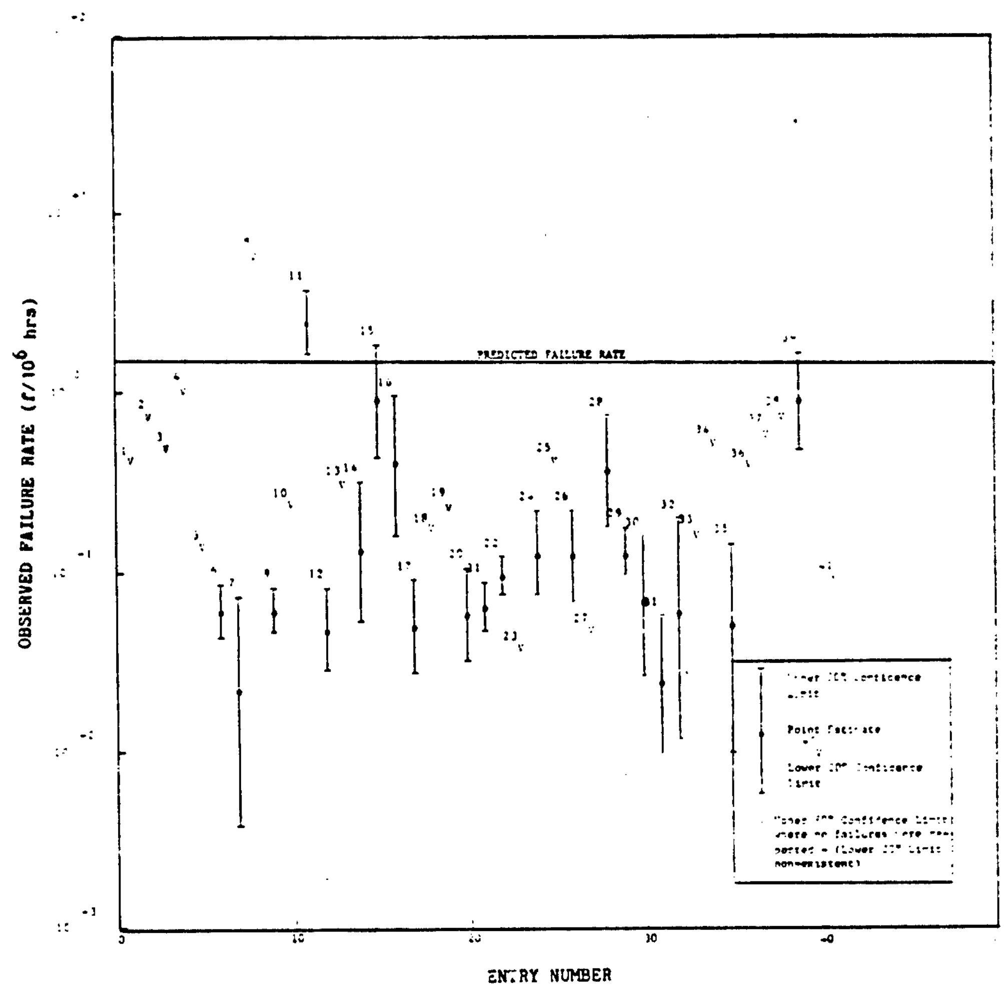


FIGURE 4.1: DISCRETE LED OBSERVED FAILURE RATES VS
MIL-HDBK-217C PREDICTED FAILURE RATES

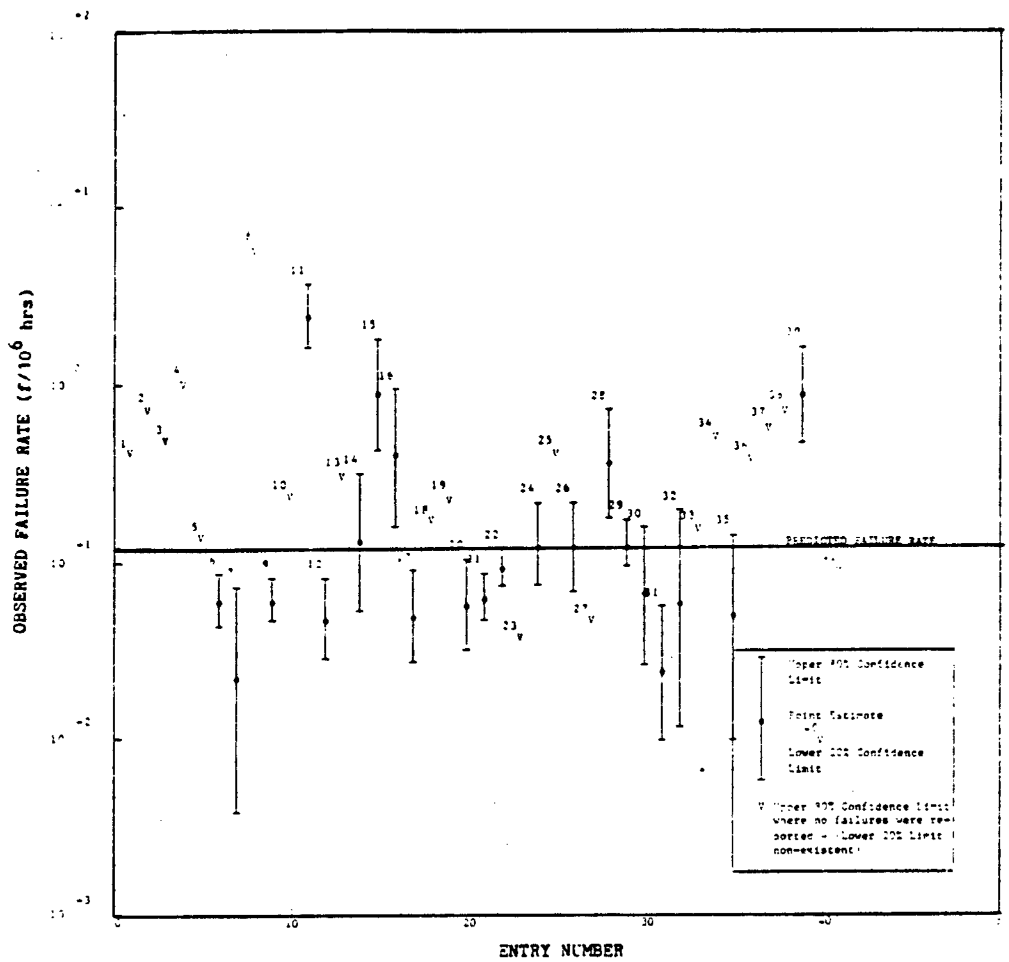


FIGURE 4.2: DISCRETE LED OBSERVED FAILURE RATES VS PROPOSED MODEL PREDICTION FAILURE RATES

TABLE 4.2

LED DISPLAY MODEL VERIFICATION DATA

Entry Number	Number Failed	Part Hours	Observed Failure Rate $\hat{\lambda}$	Chi-Square 60% Confidence Interval	λ_p Existing Model	λ_p Proposed Model
1	0	$31.5\text{x}10^6$	-	- - 0.051	1.82	0.29
2	1	$45.3\text{x}10^6$	0.022	0.004 - 0.067	1.82	0.29
3	0	$11.2\text{x}10^6$	-	- - 0.14	12.6	0.47
4	3	$7.97\text{x}10^6$	0.38	0.19 - 0.70	1.82	0.29
5	1	$3.32\text{x}10^6$	0.30	0.06 - 0.92	1.82	0.29
6	0	$7.38\text{x}10^6$	-	- - 0.22	1.99	0.22
7	13	$113.\text{x}10^6$	0.12	0.088 - 0.15	1.99	0.22
8	4	$8.74\text{x}10^6$	0.46	0.26 - 0.77	11.4	0.43
9	12	$173.\text{x}10^6$	0.069	0.052 - 0.092	1.99	0.22
10	0	$1.39\text{x}10^6$	-	- - 1.2	12.6	0.47
11	0	$4.51\text{x}10^6$	-	- - 0.36	12.6	0.47
12	0	$37.1\text{x}10^6$	-	- - 0.043	1.99	0.22
13	0	$2.12\text{x}10^6$	-	- - 0.76	0.78	0.22
14	0	$8.34\text{x}10^6$	-	- - 0.19	0.78	0.22
15	28	$113.\text{x}10^6$	0.15	0.13 - 0.18	0.78	0.22
16	2	$7.38\text{x}10^6$	0.27	0.11 - 0.59	0.78	0.22
17	7	$101.\text{x}10^6$	0.069	0.047 - 0.102	0.78	0.22
18	2	$24.7\text{x}10^6$	0.081	0.033 - 0.175	0.78	0.22
19	0	$15.5\text{x}10^6$	-	- - 0.10	1.82	0.29
20	1	$4.45\text{x}10^6$	0.22	0.045 - 0.68	1.82	0.29
21	0	$1.88\text{x}10^6$	-	- - 0.86	11.4	0.43
22	6	$39.7\text{x}10^6$	0.15	0.099 - 0.23	0.78	0.22
23	1	$3.01\text{x}10^6$	0.33	0.067 - 1.01	1.82	0.29
24	0	$11.2\text{x}10^6$	-	- - 0.14	1.82	0.29

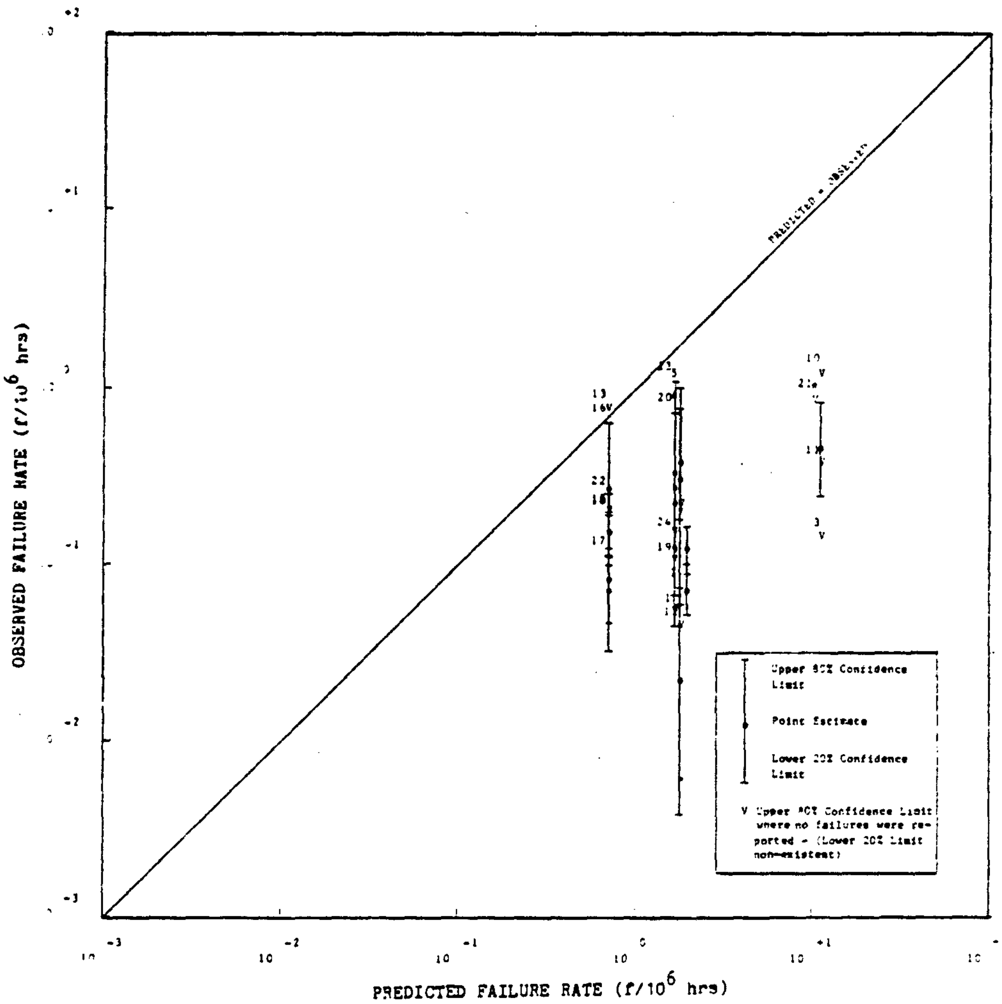


FIGURE 4.3: LED DISPLAY OBSERVED FAILURE RATES VS MIL-HDBK-217C PREDICTED FAILURE RATES

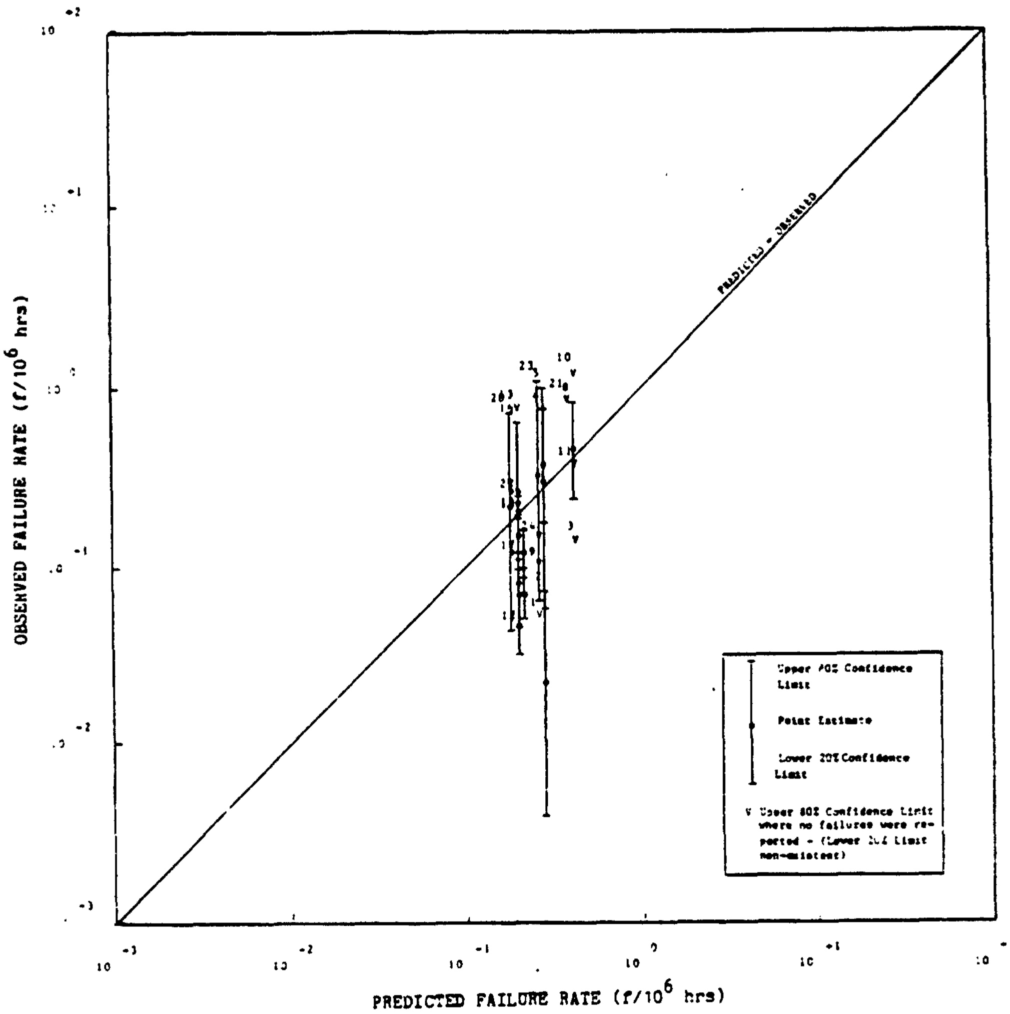


FIGURE 4.4: LED DISPLAY OBSERVED FAILURE RATES VS PROPOSED MODEL PREDICTED FAILURE RATES

TABLE 4.3

OPTOISOLATOR MODEL VERIFICATION DATA

Entry Number	Number Failed	Part Hours	Observed Failure Rate $\hat{\lambda}$	Chi-Square 60% Confidence Interval	λ_p Existing Model	λ_p Proposed Model
1	6	22,153,300	0.27	0.18 - 0.41	0.72	0.15
2	2	30,903,600	0.065	0.026 - 0.140	4.75	0.32
3	44	6,028,100	7.3	6.4 - 8.4	1.32	1.2
4	11	121,461,600	0.091	0.067 - 0.122	1.08	0.32
5	3	2,984,800	1.01	0.51 - 1.86	0.92	3.2
6	0	21,606,000	-	- - 0.075	3.2	0.15
7	1	34,866,000	0.029	0.006- 0.087	1.08	0.32
8	5	27,003,600	0.19	0.12 - 0.29	1.08	0.32
9	2	4,500,600	0.44	0.18 - 0.96	0.72	0.15
10	0	648,700	-	- - 2.5	-	0.53
11	3	10,483,200	0.29	0.15 - 0.53	-	0.53

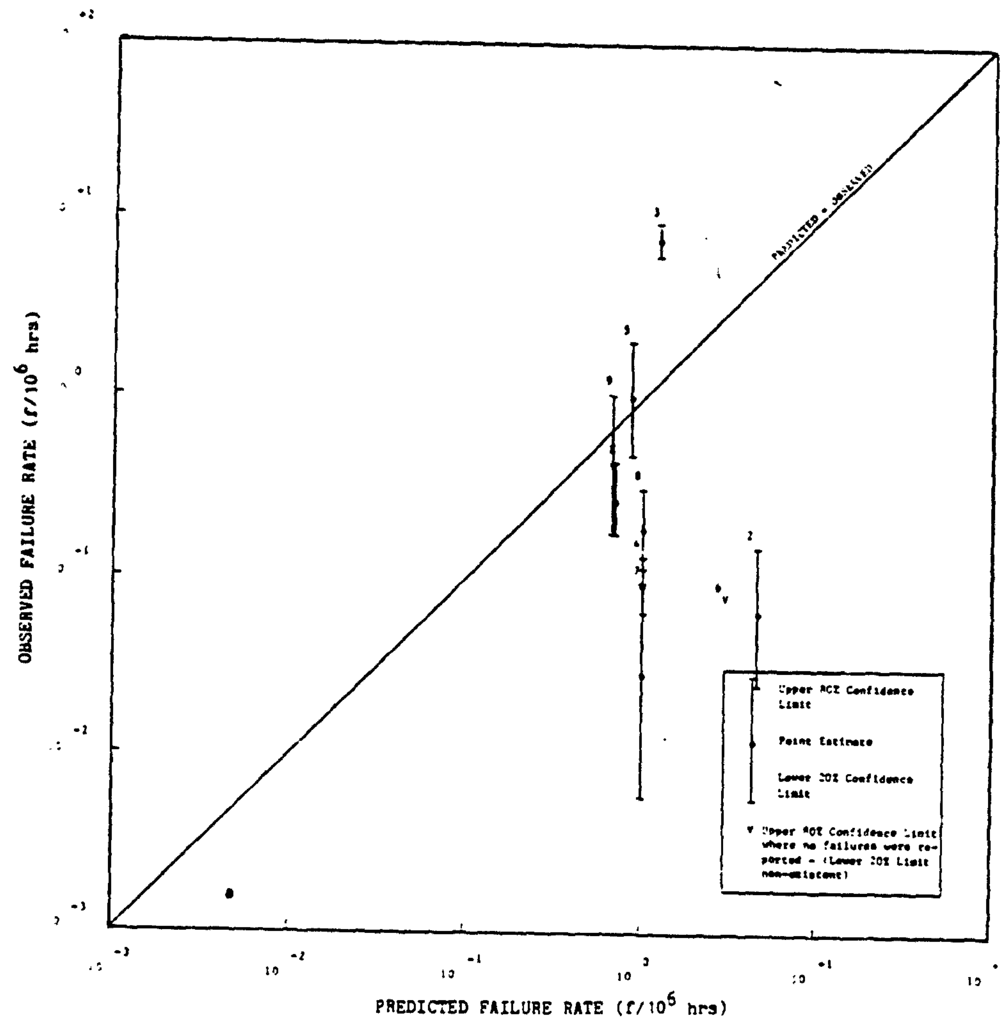


FIGURE 4.5: OPTOISOLATOR OBSERVED FAILURE RATES VS
MIL-HDBK-217C PREDICTED FAILURE RATES

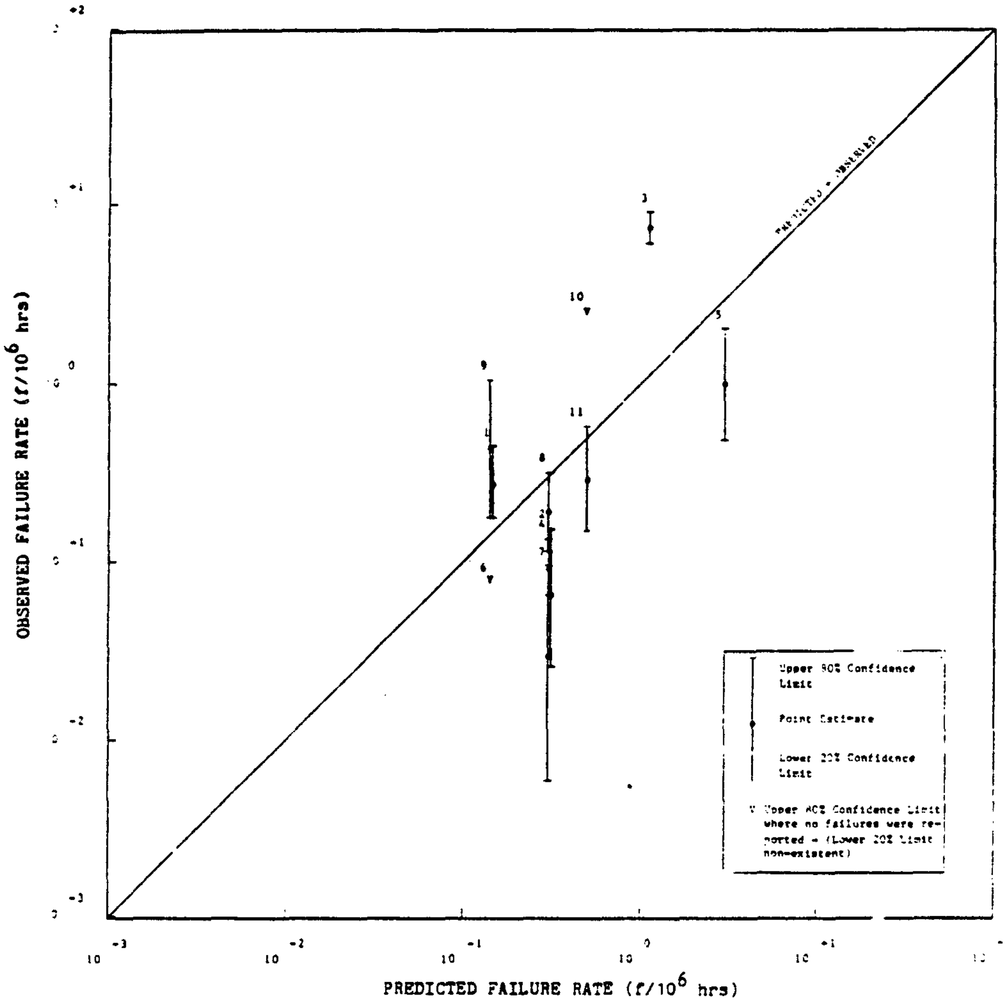


FIGURE 4.6: OPTOISOLATOR OBSERVED FAILURE RATES VS PROPOSED MODEL PREDICTED FAILURE RATES

TABLE 4.4

PHOTOTRANSISTOR MODEL VERIFICATION DATA

Entry Number	Number Failed	Part Hours	Observed Failure Rate $\hat{\lambda}$	Chi-Square 60% Confidence Interval	λ_p Existing Model	λ_p Proposed Model
1	0	859,300	-	- - 1.9	-	0.65
2	0	861,900	-	- - 1.9	-	0.65
3	4	6,656,000	0.60	0.34 - 1.02	-	0.65
4	0	248,300	-	- - 6.5	-	0.65

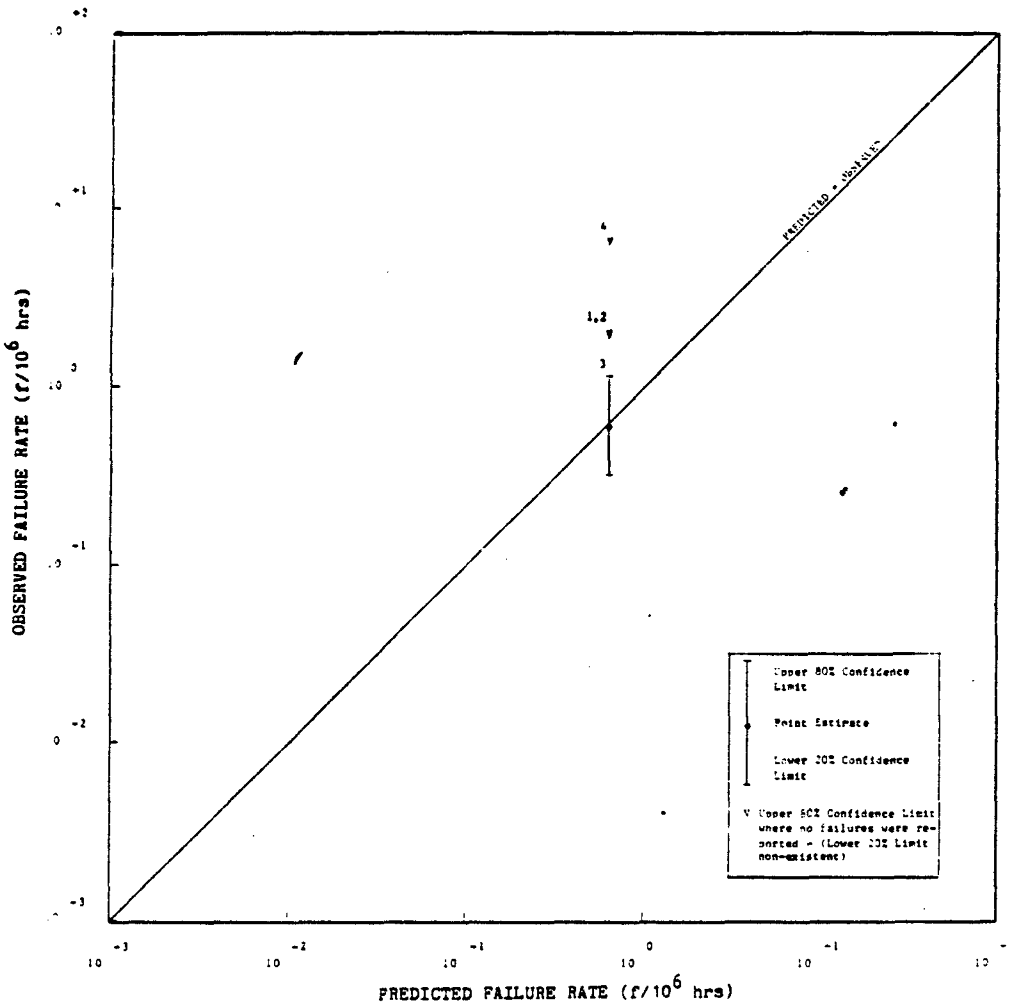


FIGURE 4.7: PHOTOTRANSISTOR OBSERVED FAILURE RATES VS PROPOSED MODEL PREDICTED FAILURE RATES

TABLE 4.5

PHOTODIODE MODEL VERIFICATION DATA

Entry Number	Number Failed	Part Hours	Observed Failure Rate $\hat{\lambda}$	Chi-Square 60% Confidence Interval	λ_p Existing Model	λ_p Proposed Model
1	0	1,396,200	-	- - 1.2	-	0.16
2	0	1,981,200	-	- - 0.81	-	0.16
3	0	248,300	-	- - 6.5	-	0.16

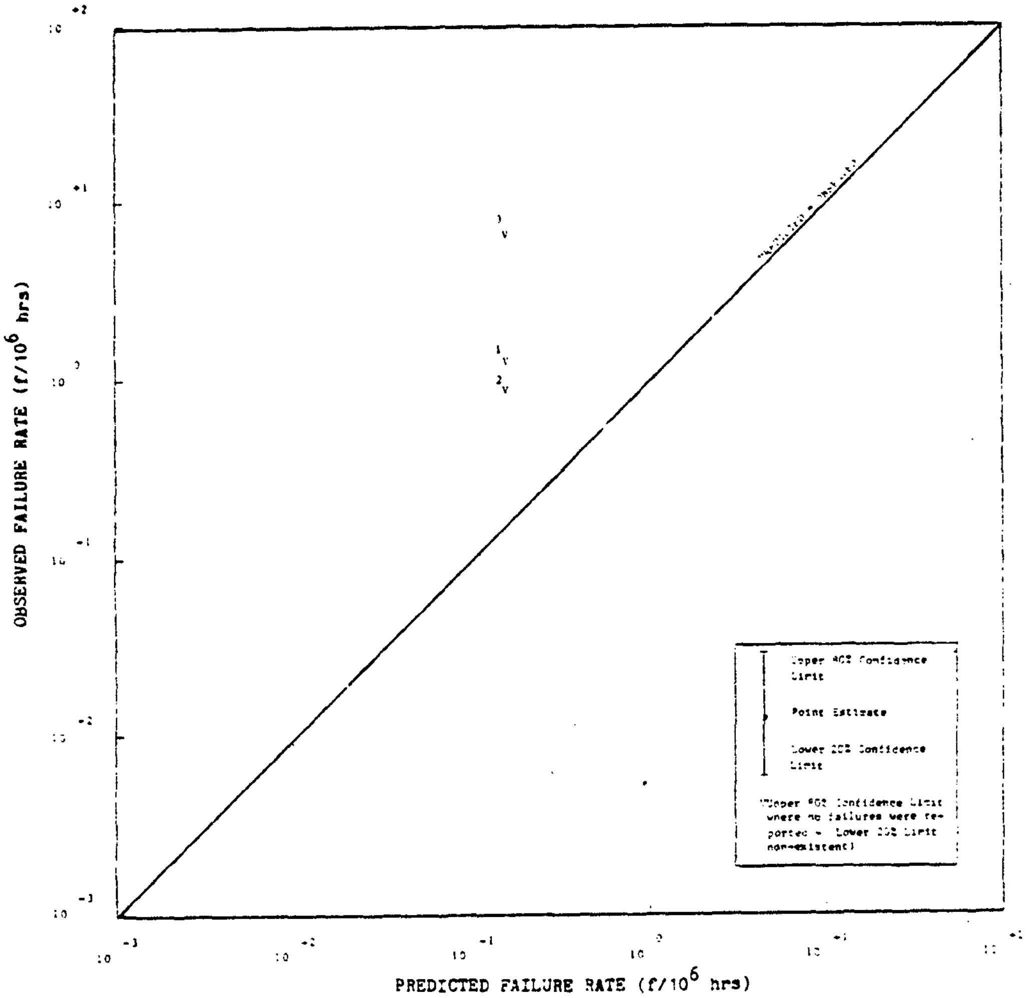


FIGURE 4.8: PHOTODIODE OBSERVED FAILURE RATES VS PROPOSED MODEL PREDICTED FAILURE RATES

SECTION 5
CONCLUSIONS

An immediate need has been identified for an accurate reliability prediction methodology for those devices and components used in fiber optic systems. The current models of MIL-HDBK-217C are deficient in several areas. Models are not available for phototransistors, photodiodes, fiber optic cables and fiber connectors, and the models for discrete light emitting diodes (LEDs), LED displays, and optoisolators yield excessively pessimistic predictions and are therefore in need of revision.

The reliability prediction models developed during the course of this study are proposed as useful solutions to the above-mentioned deficiencies.

The models have demonstrated reasonable accuracy over a variety of operating conditions and system application, and are sufficiently general to allow for simple modification or expansion at some later date. The proposed models are somewhat simpler to use than the existing models; the complex base failure rate equation used in the existing models has been replaced by a table of base failure rates by device type and complexity. A temperature dependent term π_T has been introduced to account for thermally induced changes in failure rate.

When used in conjunction with the "System Reliability Modeling," Appendix A of MIL-HDBK-217C, the proposed component reliability prediction models will permit the reliability assessment of fiber optic data links for use in comparative design analyses, reliability allocation studies, and other reliability management programs.

The models developed under this contract are presented in Section 3 in a format compatible with the present edition of MIL-HDBK-217.

The several advantages of fiber optic cables over conventional wire cables in many applications have resulted in their use in many new designs. As a result, the next few years should result in a significant increase in the amount of field data available on fiber optic components and assemblies.

For these reasons, further studies to investigate the reliability of fiber optic systems in the future as more experience data becomes available will be needed.

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